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Simulation in Automated Guided Vehicle System Design

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Declaration

No part of material described in this thesis has been submitted for award of any other degree or qualification in this or any other university or college of advanced education.

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Synopsis

The intense global competition that manufacturing companies face today results in an increase of product variety and shorter product life cycles. One response to this threat is agile manufacturing concepts. This requires materials handling systems that are agile and capable of reconfiguration. As competition in the world marketplace becomes increasingly customer-driven, manufacturing environments must be highly reconfigurable and responsive to accommodate product and process changes, with rigid, static automation systems giving way to more flexible types.

Automated Guided Vehicle Systems (AGVS) have such capabilities and AGV functionality has been developed to improve flexibility and diminish the traditional disadvantages of AGV-systems. The AGV-system design is however a multi-faceted problem with a large number of design factors of which many are correlating and interdependent. Available methods and techniques exhibit problems in supporting the whole design process. A research review of the work reported on AGVS development in combination with simulation revealed that of 39 papers only four were industrially related. Most work was on the conceptual design phase, but little has been reported on the detailed simulation of AGVS.

Semi-autonomous vehicles (SAV) are an innovative concept to overcome the problems of inflexible -systems and to improve materials handling functionality. The SAV concept introduces a higher degree of autonomy in industrial AGV-systems with the man-in-the-loop. The introduction of autonomy in industrial applications is approached by explicitly controlling the level of autonomy at different occasions. The SAVs are easy to program and easily reconfigurable regarding navigation systems and material handling equipment. Novel approaches to materials handling like the SAV-concept place new requirements on the AGVS development and the use of simulation as a part of the process. Traditional AGV-system simulation approaches do not fully meet these

requirements and the improved functionality of AGVs is not used to its full power. There is a considerable potential in shortening the AGV-system design-cycle, and thus the manufacturing system design-cycle, and still achieve more accurate solutions well suited for MHS tasks.

Recent developments in simulation tools for manufacturing have improved production engineering development and the tools are being adopted more widely in industry. For the development of AGV-systems this has not fully been exploited. Previous research has focused on the conceptual part of the design process and many simulation approaches to AGV-system design lack in validity. In this thesis a methodology is proposed for the structured development of AGV-systems using simulation. Elements of this methodology address the development of novel functionality.

The objective of the first research case of this research study was to identify factors for industrial AGV-system simulation. The second research case focuses on simulation in the design of Semi-autonomous vehicles, and the third case evaluates a simulation based design framework. This research study has advanced development by offering a framework for developing testing and evaluating AGV-systems, based on concurrent development using a virtual environment. The ability to exploit unique or novel features of AGVs based on a virtual environment improves the potential of AGV-systems considerably.

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1. Introduction

This research study was undertaken to advance the use of simulation in Automated Guided Vehicle-System development. The result was a simulation framework that covers the major AGV-development considerations using an industrially relevant simulation approach.

The research study was undertaken under the auspices of the EC-funded project INCO/Copernicus. The objective of the project was to develop Semi-Autonomous Vehicles (SAV) in materials handling and related applications. One major part of the semi-autonomous concept is to develop tools for the design process of semi-autonomous vehicles and vehicle systems. Three-dimensional simulation tools have been used to represent the vehicles and its environment for design, analysis and evaluation of SAVs from a single-vehicle perspective, and a multi-vehicle system perspective. A simulation framework was proposed for a complete applied simulation approach to the novel AGV-system development process. When the simulation framework is integrated as a part of the SAV-concept it becomes a powerful tool to rapidly develop specialised AGVS applications.

1.1 Background

Today manufacturing industry face strong competition and pressures of producing better, faster, and cheaper. This places a pressure on the production systems to continuously improve. One response to this threat is agile manufacturing concepts. This requires materials handling systems that are agile and capable of reconfiguration. Automated Guided Vehicle Systems have such capabilities and AGV functionality has been developed to improve flexibility and diminish the traditional disadvantages of AGV-systems. The objective of materials handling is to transport the right material to the right place in the right amount at the right time, with as low cost as possible.

A Material Handling System (MHS) should not be the limiting factor, and thus the bottleneck, of a manufacturing system. This objective should be achieved with a minimum if investments and operational cost. For AGV-systems the objective would be to minimise costs and maximise throughput rate.

1.2 Research Area

An automated guided vehicle system (AGVS) features battery powered, driverless vehicles moving on a guide path layout. It has programming capabilities for path selection and can be reconfigured easily to accommodate changes in production volume, product mix, product routing and equipment interfacing requirements. Additionally the guidepath can be physical, e. g. wire-guidance, or virtual only residing in the memory of the vehicle control system.

Some of the benefits of AGVs are:

- Flexible use of floor space.
- Increased flexibility in manufacturing or assembly processes.
- Computer integration and control of the material handling function.
- Availability of the vehicle is close to 24h per day depending on battery charging and maintenance time.
- Low labour cost as it is unmanned.

The number of vehicles required for a materials handling task was first addressed by Maxwell and Muckstadt (1982). This started an increasing interest in AGV-system design problems. Since 1982 much work has been reported.

A review presented by Hoff and Sarker (1998) indicates that the focus of research is:

- Multi-load vehicles, more than unit load can be transported at one time by a vehicle

- Single-loop paths, also known as tandem configuration, a guide-path layout is divided into several single loops with only one AGV per loop
- Free-path vehicles, AGVs that do not require physical guide-paths for navigation.

A review made by the author on research in AGV-system design and simulation shows that in 35 papers of 39 some type of simulation was used mostly to test and evaluate other design factors, e. g. dispatching methods, but also the evaluation of design methods. The assumptions that were made in the simulation models were in some cases overly simplifying the problem. Only four of the 39 papers reported work included some type of real industrial AGV-systems. Most work was focused on conceptual design aspects early in the design phase of AGV-systems, e. g. AGV fleet-size not considering detailed design issues. Ülgen and Kedia (1990) presented a taxonomy of the design considerations that need to be made when designing an AGV-system. There is a gap between this taxonomy and the simulation approaches reported.

The development in technology of AGVs goes towards higher functionality of the vehicles. E. g.: i) more advanced navigation systems which does not require physical guide-paths, ii) more flexible load handlers, e. g. capable of handling more than one unit load, iii) semi-autonomy, e. g. capability to avoid obstacles (Hoff and Sarker 1998, Moore et. al. 1998). One innovative concept that illustrates this development is the semi-autonomous vehicle concept, which introduces a higher degree of autonomy in industrial AGV-systems.

Traditional AGV-system simulation approaches do not fully support these developments and the improved functionality of AGVs is not used to its full power. There is a considerable potential in shortening the AGV-system design-cycle, and thus the manufacturing system design-cycle, and still achieve a more accurate solution well suited for the specific MHS task. There is a lack of structured methods and tools for the detailed simulation of AGV-systems. In other areas of manufacturing engineering, detailed simulation has become an important tool to shorten the time for development of manufacturing systems (Kosturiak and Gregor 1999, Klingstam 2001). The philosophy of Virtual Manufacturing (Lawrence associates 1994) suggests that a digital model of the whole factory should be used to develop and test changes. The digital model of the factory will then 'drive' reality and not the other way around, when simulation is used to study and improve existing production systems.

1.3 Research Aims and Objectives

The principal aim of this research is the advancement of simulation in the design of Automated Guided Vehicles. Novel AGV-systems are anticipated to become common in industry in the future, and innovative aspects of AGV-systems, e. g. Semi-autonomous vehicles, are the context of this research study. Simulation tools used are 3D graphical for manufacturing simulation. The context of the simulation tools is the Virtual Manufacturing concept where a digital model of a factory is used for development and tests of the real systems.

This can be refined into several more specific objectives, which include:

i) A literature survey in the areas of AGV-system design and simulation.

ii) To study SAV-simulation and develop a virtual environment for SAVs which supports the development of novel functionality.

iii) Identify factors and complications of industrial AGVS analysis and simulation, including large size AGV-systems.

iv) Develop a unifying framework for the design process of AGV-systems.

1.4 Thesis Outline

This thesis is divided into eight chapters. These chapters are intended to i) introduce the reader to AGV-systems and AGV-system design including novel developments in the field, ii) investigate the potentials of simulation as a tool in the design process and, iii) propose a generic methodology which combines the AGV-system design process with simulation methodology.

Chapter one provides an overview of the thesis including the research background, research objectives, the approach taken, and the organisation of the thesis.

Chapter two presents AGV-systems used in industry and the design issues of these systems. In the system perspective the design considerations are discussed which relate to system performance, system optimisation etc. The section on vehicle design focus on detailed design of vehicles, e. g. load handling devices, navigation techniques used for AGVs, control systems, sensor systems etc..

Chapter three introduces the use of simulation in manufacturing, presents in detail simulation of AGV-systems, and methodologies for simulation in the context of product and production system life cycles.

Chapter four presents the research strategy. A discussion and motivation to the choice of method and a description of the studies is provided.

Chapter five presents the results of an industrially related simulation research study with the objective of identifying factors important for AGVS-simulation of large-size industrial AGV-systems.

Chapter six presents a laboratory study of a Semi-autonomous vehicle which was used as a research platform to investigate detailed simulation of sensors and other vehicle systems. In the second part of the chapter a unifying simulation framework for the development of AGV-systems is proposed together with motivations. This is the major result of the thesis.

Chapter seven presents a simulation study and evaluation of the methodology for AGVS development. Several major design considerations are analysed in a job-shop environment.

Chapter eight summarises the research findings, presents the contributions to knowledge, and provides suggestions for future work.

2. Automated Guided Vehicle Systems in Materials Handling

AGVs can be found in most types of manufacturing industry today serving a key-role in the materials handling process. Automated vehicles are used in both job-shops, flexible manufacturing systems, and transfer-lines. A system can vary in size from a few vehicles in a limited space to over a hundred AGVs operating in layouts of several kilometres of guidepath. The size of an AGV range from small unit load vehicles to lorry-based AGVs carrying container loads (Evers and Koppers, 1996). The existing AGV application types can be categorised as: i) towing vehicles, ii) unit load vehicles, iii) pallet trucks, iv) fork lift trucks, and v) assembly line vehicles (Hoff and Sarker 1998). The number of AGV-systems sold in the USA is on average 50 systems per year with a total of 250 vehicles. The average size of the AGV-systems is 5 vehicles. In Japan 245 systems were sold during 1999. Total number of vehicles was 579 with an average of approximately 2 vehicles per system (Ward 2001). Throughout Europe there are about 1700 transport systems operating in industrial production and material distribution (Mellado et. al. 1999).

A definition of an AGV System according to Rajotia et. al. is:

> An automated guided vehicle system (AGVS) features battery powered, driverless vehicles moving on a guide path layout. It has programming capabilities for path selection and can be reconfigured easily to accommodate changes in production volume, product mix, product routeing and equipment interfacing requirements (Rajotia et. al. 1998c).

According to Hoff and Sarker an AGV is :

> a driverless vehicle that performs material handling transportations within a facility. The material handling vehicles are usually of six major types that include unit load, towing, pallet truck, fork lift, light load, and assembly line vehicles. They operate on battery power that provides locomotion as well as power to an on-board computer (Hoff and Sarker 1998)

Today, many AGVs have powerful on-board microcomputers that increase local guidance capabilities and the flexibility needed to accommodate any changes on the shop floor. Recent advances in the technology permit vehicles to travel without any physical guide path, and these vehicles are known as free-ranging automated guided vehicles. Other names used in literature for free-ranging vehicles are free-moving and free-path vehicles. Dead reckoning, inertial guiding, and ultrasonic image processing are examples of such systems. With virtual flow paths, the system controller can easily alter the guide path layout of the system to reflect the material flow demands. The virtual flow path does indeed provide more flexibility for the AGV-systems in that vehicles can travel on both directions of the path (Shen and Lau 1997). Therefore, not only should the direction of the flow path be easily changed as the need arises, but the computational time required to obtain a new flow path should also be within a reasonable range.

In materials handling AGV-systems provide flexibility in terms of: i) paths for material flow, ii) use of floor space, iii) in manufacturing or assembly processes. Additional benefits are integration of computer control of the material handling function, availability of vehicles as they can work almost 24h per day, and low labour cost since they are unmanned. (Arifin and Egbelu 2000)

Two of the most important characteristics of production systems are flexibility, i. e. number of types of products, and productivity, i. e. number of products produced per time unit. One of the traditional production layouts is the job shop with a functional layout, where machines and operations are located according to function. Modern manufacturing systems basically use three manufacturing principles: (Askin and Standridge 1993)

(i) Job shop

(ii) FMS

(iii) Transfer line

These principles use either the batch type or flow-line production method. A job-shop is traditionally the most common production layout. The machines are organised according to function and the batch type principle is used for material flow. These flows are often complicated with much transportation between workstations. The advantage of this approach is a flexibility to handle many different batches. Disadvantages are typically long production lead-times due to high transportation and queuing times, and lower throughput and utilisation of machines. The use of AGVs in job-shops involves a complex control problem due to a large number of routes between stations and sometimes many human operators in the area, while much transportation may motivate an automatic material handling system

The flexible manufacturing system (FMS) consists of a number of machine tools interconnected by a transportation system, using the flow-line principle. Besides the programming of machine tools, the designated route and handling of the part has to be included. Since the flow-line principle is used, high production rates can be obtained. AGVs are nowadays commonplace in FMS layouts. The control of an AGVS can be well integrated with the production control of an FMS.

The transfer line, being a flow-line, is based on a mass production principle. The workstations are usually fixed type automated custom-made machines, which are seldom reconfigured. High production rates can be obtained at a minimum cost. The loss is in flexibility with a low number of products and variants. Transfer lines have a straightforward material flow, often with automatic material handling systems. AGVs used in transfer lines are typically assembly carriers.

2.1 Summary of Research in AGV-System Design and Simulation

The use of AGV-systems have increased during the last decades resulting in an increased interest in AGV-system design. In a review of AGV research Ülgen and Kedia (1990) presented the following objectives of research work before 1990:

- Determine minimum number of AGVs required.
- Minimise total travel of loaded vehicles.
- Minimise total travel of vehicles (loaded and unloaded travel).

A more recent review by Hoff and Sarker (1998) indicates a change in focus towards:

- Multi-load vehicles, more than one unit load can be transported at one time by a vehicle

- Single-loop paths, also known as tandem configuration, a guide-path layout is divided into several single loops with only one AGV per loop
- Free-path vehicles, AGVs that do not require physical guide-paths for navigation.

A review made by the author on research in AGV-system design and simulation shows a similar result. The emphasis of the review was however to study the combined approach of AGV-systems and some type of simulation. Of interest in the review was:

(i) the objective of the research

(ii) in what way has simulation been used,

(iii) which software tools have been used

(iv) what assumptions about the simulation model was made, and

(v) did the research include work on real AGV-systems

A total of 39 papers were reviewed, many of the objectives where the same as previous reviews, determine required number of vehicles, minimise total travel of vehicles, but also deadlock prevention and other objectives. Some approaches were more frequent than in previous reviews namely:

- use of bi-directional guide-path layout and approaches associated to solve the more complex control problems
- novel dispatching and scheduling methods to improve system performance, in some cases to plan collision-free routes
- improved simulation methods and tools to overcome inaccuracies of AGV-system simulation and to increase the problem domain for simulation approaches
- general simulation approaches for AGV-system design..

The one most common objective was to decide the number of vehicles required to fulfil a materials handling task. The complete review summary can be found in Appendix 1.

It appears to be a common understanding in the reported research about AGV-system design that there is a large potential in:

(i) use of bi-directional paths, if an appropriate transport control is achieved,

(ii) use of multi-load vehicles as this can considerably decrease required number of AGVs and increase maximum throughput,

(iii) use of free-path vehicles to increase flexibility, if this can be motivated (Bilge and Tanchoco 1997, Hoff and Sarker 1998).

In 35 of the papers some type of simulation was used mostly to test and evaluate other design factors, e. g. dispatching methods, but also the evaluation of design methods. A total of six software tools can be found in the review, however some researchers have developed their own simulation software and some papers do not include this information.

The assumptions that were made relating to simulation of AGV-systems were in some cases overly simplifying the problem:

- no acceleration or deceleration was assumed
- no recharging of batteries assumed
- no blocking was assumed to occur
- the location of idle vehicles was not included
- the presence of possible interruptions e. g. obstacles blocking the path were not included.

Only four of the 39 papers reported work including some type of real industrial AGV-systems. Most work was focused on conceptual design aspects early in the design phase of AGV-systems and there are few papers that include detailed design issues in a comprehensive way. For many AGV-system applications or conceptual design studies some of the assumptions described will arguably not have a large influence on the result. However, if they are combined the correlation between many of the AGV-system design variables can make the result less accurate and less trustworthy. E. g. the three first assumptions is most likely to decrease the assumed number of AGVs required for a given production system. This leads to a higher number of AGVs required for the real system, which consequently can lead to an increase in blockings which even more increase the requirement for AGVs etc..

The development in technology of AGVs goes towards higher functionality of the vehicles. E. g.: i) more advanced navigation systems for free-moving AGVs not requiring physical guidepaths, ii) more flexible load handlers, e. g. capable of handling more than one unit load, iii) semi-autonomy, e. g. capability to avoid obstacles. Traditional AGV-system simulation approaches do not fully support these developments and the improved functionality of AGVs is not used to its full power. There is a considerable potential in shortening the AGV-system design-cycle, and thus the manufacturing system design-cycle, and still achieve a more accurate solution well suited for the specific MHS task. There is a lack of structured methods and tools for the detailed simulation of AGV-systems. In other areas of manufacturing engineering, detailed simulation has become an important tool to shorten the time for development of manufacturing systems (Kosturiak and Gregor 1999, Klingstam 2001). The philosophy of Virtual Manufacturing (Lawrence associates 1994) suggests that a digital model of the whole factory should be used to develop and test changes. The digital model of the factory will then 'drive' reality and not the other way around, when simulation is used to study and improve existing production systems.

There is a need for a structured framework or methodology to overcome the risks and problems of using simulation for the detailed AGV-system design. There is also a need for a framework in the use of simulation of AGV-systems with novel functionalities. This type of simulation is not covered in the research literature.

2.2 Design of Automated Guided Vehicle Systems

The design of AGVS is a non-trivial task with many correlating factors to consider. The integration of machines and materials handling systems also adds to the complexity. It is still of great importance to have a well balanced AGV-system to fully utilise the production system.

Figure 1 shows the main options to be made for the physical structure of an AGV-system. These include the guidepath configuration, choice of vehicle type and load capacity, and navigation method.

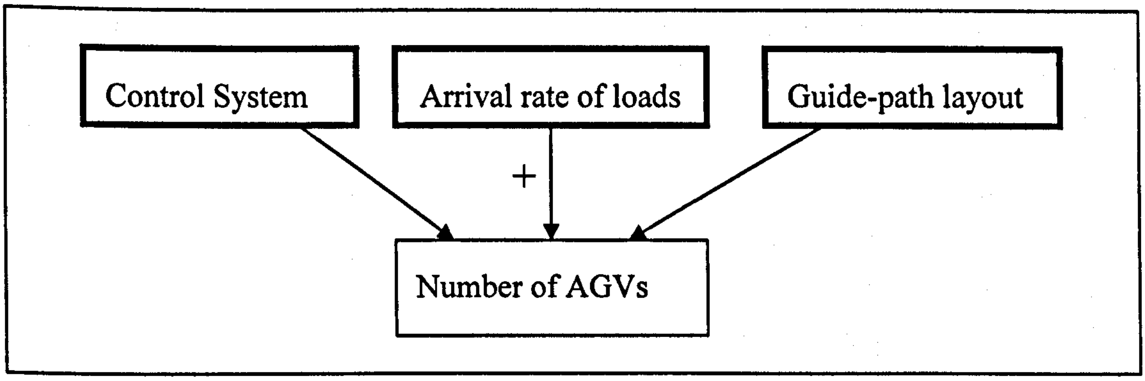

Figure 1, Deciding Number of AGVs. The figure shows the main factors that influence the required number of AGVs for an MHS. The type of control system and operational policy can either lead to an increase or decrease. Higher arrival rate and larger layout typically results in an increase in the number of AGVs.

The widespread use of AGVS in manufacturing and other applications has generated much interest in the development of both simulation and analytical tools for designing AGV-systems. One of the most important design variables is the guide-path layout. It has direct impact on the efficiency of vehicle dispatching and scheduling (De Guzman et. al. 1997).

The physical structure of an AGV-system is most often a guide path layout (physical or virtual), a control system, pick-up and delivery stations, recharging stations, and vehicles. Other items as artificial landmarks for navigation are also part of the AGV-system. The second set of factors influencing the operation of an AGV-system is the vehicle management. According to Taghaboni and Tanchoco (1988), the primary vehicle management functions for an AGV-system can be defined as:

- *Dispatching*, the process of selecting and assigning tasks to vehicles.
- *Routing*, the selection of the specific paths taken by vehicles to reach their destinations.

- *Scheduling,* the determination of the arrival and departure times of vehicles at certain points along their prescribed routes to ensure collision-free journeys.

In the physical design of an AGV-system the major consideration to be made is the guide-path layout and location of pickup and delivery stations. The objectives in the guide-path design are multifaceted such as minimisation of transportation cost, inventory cost, vehicle cost, travel distance, system time, and deadheading (dead travel time). In all these objectives, the ultimate goal is either minimisation of time and cost or maximisation of the throughput rate. Approaches range from simple logic to sophisticated mathematical problems such as integer programming formulation, branch-and-bound approaches, heuristics and simulation (Hoff and Sarker 1998). These are described in detail in section 2.2.2.

There is a strong correlation between the guide-path design and operational design factors. Sinriech and Tanchoco (1992) have found that regardless of the guide path objective, the guide path design directly affects the operational performance of the AGVs because of the interaction with the dispatching rules that may cause vehicle congestion or guide path blocking.

There are however many other factors influencing AGVS-design such as limited physical space, limitations in the production system layout etc.. Obviously the process of designing AGV-systems is carried out in conjunction with and/or strong influence by other processes in manufacturing design. In most cases the facility has already been laid out and the pickup and delivery stations and idle locations become the two design questions in guide path design which can be set.

The literature review indicates two main perspectives that can be taken on the design of AGVS, which is conceptual design and detailed design. The emphasis of research activity have been on conceptual design. Only four papers of 39 report work made relating to an implemented real AGVS. Most often the authors have focused on one or a few of the design factors of an AGVS, the most common of these is deciding the number of vehicles required to fulfil a materials handling task. Other factors that have received much attention are the use of bi-directional guide-paths, vehicles able to carry more than one load at one time, and vehicles navigating without physical guide-paths. A summary of the literature review can be found in Appendix 1.

The use of simulation is wide-spread, most of the reported work use simulation for some purpose. There exist a wide variety of simulation approaches and 11 numbers of simulator software have been found. These are typically used for conceptual design, and to evaluate the performance of non-simulation approaches, i. e. heuristics and mathematical methods. These simulations often make assumptions disregarding certain aspects of an AGVS design. These assumptions can strongly influence the validity of the simulation models and the conclusions drawn from them.

Simulation in manufacturing systems including AGV-simulation is presented in detail in chapter 3.

2.2.1 Conceptual and Detailed Design of AGV Systems

The methods used for designing AGV Systems can be categorised in conceptual and detailed design. Most of the analytical methods presented in this thesis are conceptual as they provide indications or 'rules-of-thumb' for the AGVS design problem while simulation also can be used as a tool for detailed design which verifies the conceptual design.

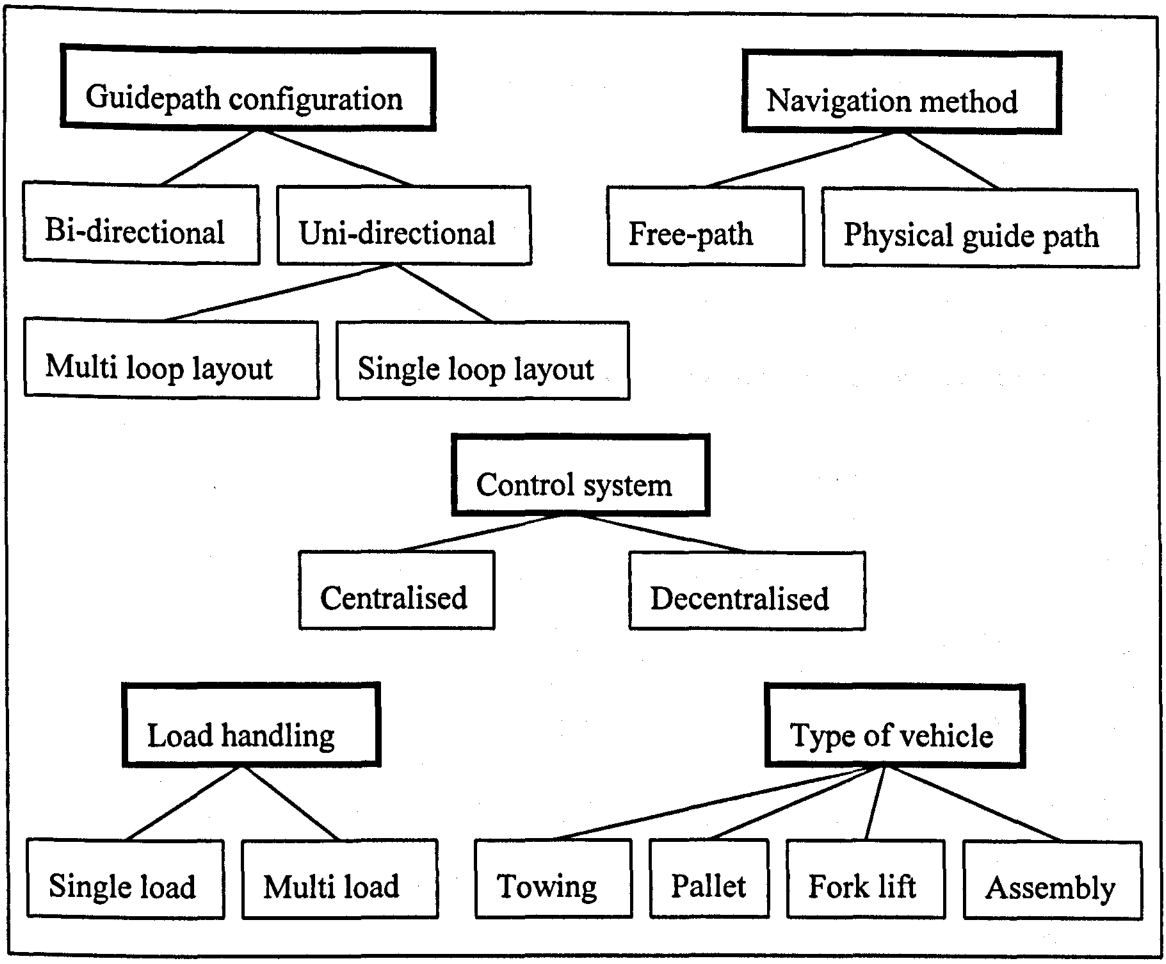

Figure 2, Physical design considerations of an AGV-system. The figure shows the main options to be made for the physical structure of an AGV-system, and examples of their subcategories.

One of the main questions in AGVS design has been to on a conceptual basis decide the required number of AGVs for a system. Information needed is the arrival rate of loads and some information on guide-path layout, as presented in Figure 2. There is a strong interrelation between control system parameters and guide-path design. A balanced combination can considerably decrease required number of AGVs in comparison with a less successful design. To keep the cost of an AGVS low it is of great interest to keep the fleet size as small as possible for a given MHS and level of service. The potential design parameters to achieve this goal are either related to the control system or the guide-path layout.

2.2.2 Approaches and Methods to Solve the Design Problem

The scientific method in its simple form is the statement of a hypotheses, and based on observations either the support or rejection of the hypotheses.

A detailed description of the scientific method in the context of this thesis is: i) observation, ii) statement of a problem iii) development of alternative solutions, iv) choice of optimal solution based on experiments, v) verification by implementation.

A number of problem types can be solved using Operations Research, according to Gillett (1976) most of these problems can be categorised as:

- Sequencing problems, the placement of parts in a certain order
- Allocation problems, the allocation of resources to activities
- Route problems, choosing a route from a start to an endpoint.
- Exchange problems, the replacement of defect or deficient equipment
- Stock level problems, the establishing of stock levels
- Queuing problems, the use of limited resources
- Competition problems, objects competing for a resource
- Search problems, the search for necessary information for decision making

The problems often occur in combinations, e. g. in simulation of complex systems such as AGV-systems all eight categories can occur.

There are many alternative solution techniques for these problems. Some are traditionally associated with operations research:

- Linear, non-linear, 0-1, and dynamic programming
- Network planning
- Decision, game, and queuing theory
- Simulation

The main reason to choose simulation rather than analytical methods is that complex problems typically 'run out' of analytical methods and simulation becomes the remaining alternative. It also provides a representation of the studied system with fewer simplifications, at the cost of a generic solution.

Lee et. al. (1990) states that a majority of the problems regarding AGVS simulation are qualitative rather than quantitative. This implies that mathematical analysis is only sufficient to give a guideline to the solution of the overall design of an AGV-system. Since it is almost impossible to optimise the design, evaluation techniques must be used to measure the performance of the system.

Performance indicators which may be used to compare alternative layouts and operational control policies are, e.g. the throughput, transportation lead times, the production lead time of an order set, and robustness against dead-lock situations. (Mantel and Landeweerd 1995)

According to Sun and Tchernev (1996) there are mathematical modelling approaches to select the optimal guide path layout and the location of load transfer points from the point of view of material flows between certain workstations. However, the assumptions of many flow-path based solution approaches are often unrealistic. These approaches assume a certain flow of material between workstations which can be stated in a matrix form. The flow can be positive or negative depending on the flow direction. According to Shen and Lau (1997) the flow path based formulations consider only static cases where the material flows from one station to the other are assumed to be known and ready at the beginning of operation. For real life operations, this can never be the case. The waiting time for the materials may not be the minimum resulting from these models due to the lack of consideration of dynamic behaviour, such as random arrival.

Thus some aspects can only be chosen and estimated by a detailed simulation. From the system design point of view the simulation can be used for:

- comparing compatible alternative MHS guide path decisions, complex node configuration (crossings) and the location of machining centres and their pick-up and drop-off stations

- to evaluate the required number and type of vehicles to satisfy a material handling function for a given technology system in dependence of the input and output material flows
- to choose the vehicle control strategy.

The correlation between these parameters, like the interdependence between the guide path layout, the traffic, and the zone control, makes the design more complicated. One of the most important design issues for AGVS operation efficiency is the configuration of the guide path layout.

Firstly, for very large size problems, it is not always trivial to find out a feasible guide path layout configuration. Secondly, the number of all possible configurations may be very high. E. g. only 38 tracks have 2 to the power of 38 possible configurations. The number of configurations is too large to be evaluated by simulation. From this point of view, a good design process should consist of generating an optional guide path network using a modelling optimisation approach and then testing the design by simulation for evaluating the AGVS performance.

The AGV guide path layout problem was also studied by Gaskins and Tanchoco (1987) as a zero one integer linear programming problem. They presented an approach for determining the optional flow path in the node arc network, where the nodes present pick-up/drop-off stations and aisle intersections and the arcs are guide path connected with the nodes. The objective is to find the flow path in the unidirectional layout which will minimise the total travel of loaded vehicles. Two types of constraints are formulated:

- constraint to guarantee that every node has an entry and a leaving node, i.e. connectivity constraints,
- constraint to ensure that each node is reachable from any node, i.e. reachability constraints.

2.2.3 Taxonomy of AGV System Design

Ülgen and Kedia (1990) made an extensive review of research in the area and they have presented a taxonomy for AGVS which can be found in a modified form in Table 1. The functionality of a vehicle will depend on e. g., navigation techniques, control program, hardware equipment as actuators and types of sensors, and wheel configuration. This is decided during the design phase. At the process level, the type of vehicle is decided and following that, the type of drive, steer, load handler, navigation and other equipment considerations are made. For the AGVS to work optimally the facility considerations are also important, such as number and location of buffers, storages, and production layout. This also influences the decisions made at the next level. The workstation considerations include production layout, location and configuration of workplaces, but also processing times. Its valuable to distribute processing times evenly over workplaces. This is strongly inter-linked with the transportation times, number of job types, lot sizes, and intensity of flow collisions. At the lowest level of decisions to be made are the operational aspects of the AGVS, the travel and schedule-related considerations, which are important for efficient use of the system. At this stage detailed decisions regarding type of flowpaths, path layout etc. are made. Also job and vehicle dispatching rules and sequencing of move requests are decided. This taxonomy supports a systematic approach to the design of AGVS.

Level	Decision variables	Level	Decisions variables
Process focus	Vehicle type (AGVS)	*Workstation considerations*	Multiple/parallel workstations
	Unit Load Vehicles		Processing time
	Fork Trucks		Transportation times
	Assembly line vehicle		Number of job types
	Towing Vehicle		Intensity of flow collisions
Equipment considerations	Differential or steered wheel control	*Travel-related considerations*	Shortest time/distance
	Traffic management / Navigation		Type of flowpath
	Navigation techniques/sensors		Fixed or variable travel-time
	Guidewire, free-roaming or combinations		Path layout
	Forward sensing		Zoning
	Central / onboard zone control		Number of path segments
	Combination control		Battery change segments
	Guide path frequency or path switch method of routing		Blocking/Congestion
	Guide path, uni- bidirectional or mix		Presence of bypasses
	Load carrying and transfer (forklift, power roller etc.)		Travel speed
	Vehicle dispatch (central, local, onboard etc.)		Loading/unloading time
			Operating policy, when idle stop, cruise or park
Facility considerations	Number of workstations, location	*Schedule-related considerations*	Static or dynamic scheduling
	Number of buffers, location		Sequencing of move requests
	Storage system parameters		Intersection control, zoning
	Number of kits		Rules for:
			Contention (fifo, closest, priority)
			Idle vehicle disposition (stop, cruise)
			Job selection by AGVs
			Vehicle selection

Table 1, Modified AGV-design taxonomy. The table shows a modified version of the Hierarchical Taxonomy of Design and Scheduling for Automatic Guided Vehicles by Ülgen and Kedia (1990)

2.2.4 Deciding Vehicle Fleet-Size

Design of an AGV System involves deciding a number of parameters. The fleet-size of the system, i. e. number of vehicles, has received much attention in the research community, and there are several methods proposed to decide this parameter. Figure 3 shows the factors that in some way influence the required number of AGVs.

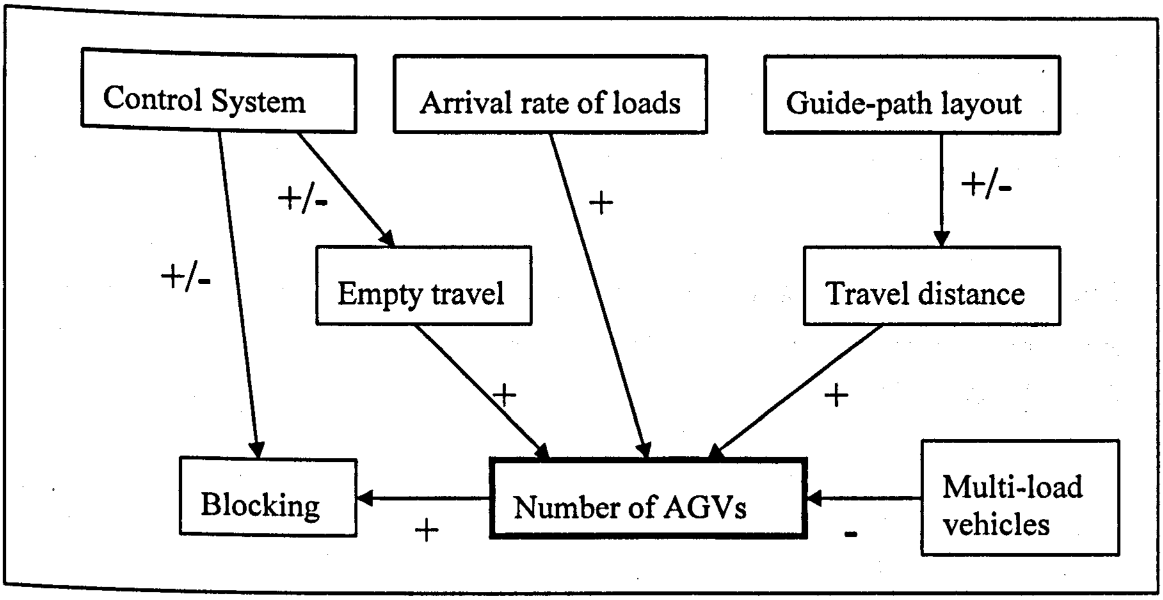

Figure 3, Factors influencing the required number of AGVs. The type of control system and operational policy can either lead to an increase or decrease to empty travel and blocking which influence the AGV numbers. Higher arrival rate and larger layout typically results in an increase in number of AGVs.

Maxwell and Muckstadt (1982) did pioneering work in analytical modelling of operational features of an AGVS. In an environment comprising primarily of assembly operations for finished products, they proposed a time-independent model to estimate the minimum number of vehicles required to support the material handling needs. The empty vehicle travel was estimated by computing the net flow at each P/D station as the difference between the total number of unit loads delivered there and the total number of unit loads picked up from there. It represented number of empty trips into or out of that station. The station with positive net flows had empty trips available to be assigned to other stations with negative net flows. A standard transportation problem was formulated which assigned empty vehicle trips between various stations minimising the total empty vehicle travel time.

According to Arifin and Egbelu (2000) simulation has been proven to provide an accurate number of vehicles required. However, simulation is time consuming and expensive to consider at the early planning stage, when only a rough estimate is required. An alternative to simulation is the use of an analytical model. An analytical model is defined as a mathematical relationship that captures the most significant factors or attributes from the production facility to determine the number of AGVs required. When properly designed, analytical methods can be provide reasonably accurate estimates of vehicles requirements in an automated guided vehicle system.

The method of Arifin and Egbelu is based on regression analysis in which some key system parameters identified to influence vehicles requirements are used in fitting a regression equation of the form $y = f(x1,x2,x3\ldots,xn)$, where y is the estimate number of vehicles or the dependent variable, and x1 ...n are the independent variables or system parameters, and $\in$ is the error term associated with the equation.

The general form of a regression model can be written as $y = f(x) + \in$ where: x is a vector and $\in$ is the error term.

To develop the model, the following tasks are performed.

- Identify the system factors or parameters that are suspected to affect vehicle requirements.
- Collect data on a sample of AGV-system applications with regard to both the observed vehicle requirements and the values of the suspected parameters of independent variables.
- Analyse the data to fit a model.
- Eliminate insignificant independent variables, and determine the final estimating model.

Simulated data was employed in place of actual industrial data to achieve a sufficient number of AGVS designs.

This implies that industrial data are actually simulated observations that have seen implementation.

For a given facility, the following parameters were considered as influencing fleet size requirements:

- number of workcenters;
- total vehicle routing distance (total length of AGV route);
- number of intersections (conflict nodes) and number of nodes;
- maximum machine utilisation;
- total loaded and empty travel distance;
- layout complexity.

A total of 32 different facility layouts were simulated in the study. Most of the layouts were collected from published papers involving AGVS. In general, the performances between the regression models do not differ significantly. This suggest that using the multiple regression approach produces good results.

Although not intended to take the place of detailed simulation analysis of a facility under consideration for AGVS application, the regression model determined in this study provides a reliable estimate that is sufficiently good for the initial phase of a system design. Apart from the reliability of estimates, another strength is the simple form of the regression model

The authors Shen and Kobza (1998) focused on finding the minimum number of vehicles needed in an automated guided vehicle system (AGVS), considering the impact of vehicle dispatching rules, such that the chance of a vehicle-initiated situation occurring is less than a given very small threshold specified by the system designer. The designer of a material flow system is concerned not only with the specifications of individual system components, but also the associations between the components and the interactions of the material flow system within the manufacturing system itself.

Rajotia et. al. (1998a) presents an analytical method that involves the consideration of load handling time, empty travel time, and waiting and blocking time. Load handling time is computed from given parameters. Determination of empty vehicle travel is difficult due to the inherent randomness of an FMS. The constraints are in the form of upper and lower bounds placed on the total number of empty trips starting from or ending at a load transfer station. Achievement of high performance from an AGVS is influenced by several design and operational control issues. These include specifying the type and number of vehicles to be employed, specifying appropriate guide configuration together with locating load transfer stations, locating vehicle buffering areas and specifying their holding capacity, specifying vehicle dispatching and routing strategies, managing traffic, specifying unit load sizes, specifying central and/or local work-in-process storage capacity, etc..

Malmborg (1991) suggested a scheme for computing empty vehicle time which is opposite to the approach taken by Maxwell. Important differences arise on both counts number of empty trips and travel time of each such trip. The frequency of empty trips was based on total number of loads delivered at or picked up from each station rather than the net flows. Further, instead of minimising empty travel time, Malmborg's scheme maximised it. It meant that each vehicle, after having unloaded its load at a delivery station and become empty, was routed to the farthest away station. The total empty vehicle travel time thus obtained was considered by Malmborg as an upper bound solution as opposed to the lower bound one of Maxwell's model. Further, he argued that actual empty travel would be a weighted average of these two bounds. The weighing factor would be a function of vehicle dispatching strategies in operation, and a management defined constant.

Sinriech and Tanchoco (1992) developed a multi-criteria optimisation model considering costs and throughput to determine the AGV fleet size. They used a trade-off ratio between the two goals and introduced management decisions tables to enhance the solution procedure. These time elements should be minimised, if not eliminated completely. The dynamic behaviour of AGVS may necessitate these time components to be present and also render them incalculable in advance. They cannot be computed a priori because they are dependent upon the AGV fleet size, a parameter which is to be determined in the first place. The greater is the number of vehicles operating on the shop floor at any time, the more is the likelihood of their getting blocked as well as waiting for transport calls. Other factors on which vehicle waiting and blocking times depend are vehicle dispatching and routing strategies, guide path layout, and vehicle clearance procedures at intersections. Vehicle blocking phenomenon is manifested more frequently in an AGVS consisting of bi-directional arcs.

On the other hand, Malmborg's model results in over-estimation of the fleet size since it attempts to maximize empty vehicle travel time. The models suggested by Kuhn, Beisteiner-II, Kulweic and the proposed model present a somewhat more realistic picture of the situation when compared with the rest of the models (Malmborg 1991).

Mantel and Landeweerd (1995) claims that the number of AGVs required in a system is the sum of the total loaded and empty travel time and waiting time (among other things due to congestion) of the AGVs in a busy time period, divided by a time an AGV is available during that period.

Nakano and Ohno (2000) proposes an integrated analytical/simulation approach for designing an automated guided vehicle system (AGVS) which consists of AGV's, machines with input buffers and a dispatching station in a just-in-time (JIT) environment.

Analytical approaches which model the systems by means of mathematical equations often need unrealistic assumptions, while simulation models are often time-consuming and do not provide exact solutions. Nakano and Ohno starts with using four hybrid models originally proposed by Shantikumar and Sargent. Their analytical and simulation models are independent, and their corresponding solution procedures are combined during problem solving. Class four type in their hybrid models is defined as a model in which a simulation model is used as an overall model of the total system, and it requires values from the solution procedure of the analytic model of a portion of the system for some or all of its parameters. Most of conventional hybrid approaches employ a simulation model as an overall model of the total system and an analytical model only for determining some of its initial parameters of the simulation model.

The workstations are numbered 1 through N and process N types of parts. Workstation i consists of machine i and input buffer i. Part i is processed only at machine i.

AGVs deliver part i to workstation i and are assumed to carry one unit at a time.

Vj: travel time from dispatch station to station j,

Xj: return travel from station j to dispatch station

Nj: total travel time as Nj=Vj+Xj

1/Ui : distribution of processing time of part i at machine i.

Bi : capacity of input buffer in front of machine i.

Let ui be the utilisation of machine i and ui_mean the planned utilisation of the machine i that is determined from a forecast demand of the completed components of machine i.

The components are dispatched to the withdrawing machine that has the maximum value of ui_mean - ui among withdrawing machines.

An alternative to increasing AGV fleet size is to use vehicles with multiple load-carrying capacity. A multiple-load vehicle can pick up additional loads while on the way to accomplish a previously assigned task. According to Bilge and Tanchoco (1997) there are many advantages of decreasing unit-load size. Machine utilisation, flow time, and work in process can be improved because parts that belong to the same job can be processed simultaneously at different workstations.

Design parameters influencing AGV-system capacity include facility layout, guidepath layout and its characteristics, vehicle fleet size, work-in-process storage capacities, and handling and storage equipment parameters. Operating parameters influencing capacity include product mix and routings, dispatching and traffic management strategies, and WIP storage disciplines.

2.2.5 Vehicle Guide-path Design

Hoff and Sarker (1998) presented a review of recent work on the design of AGV guide paths and dispatching rules, including related issues such as idle vehicle location, and location of pickup and delivery stations. Different types of guide paths and related layouts, including optimal and heuristic approaches to the path design, are reviewed.

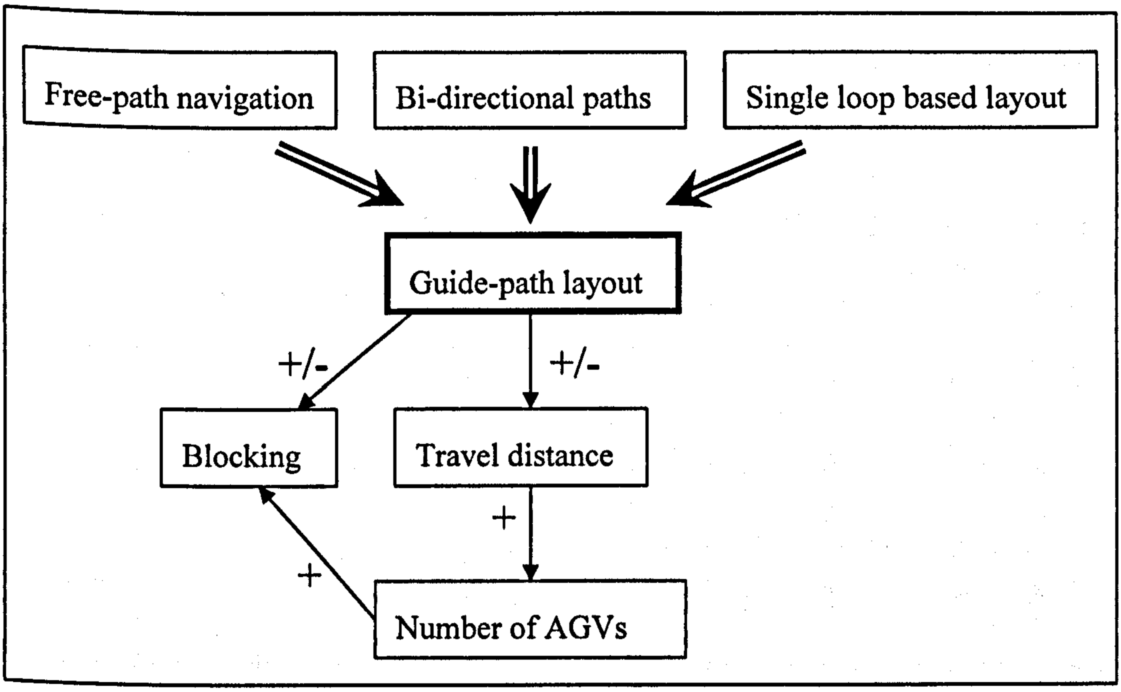

Figure 4, Novel design factors influencing the guide-path design. Performance of a layout is typically indicated with throughput, transportation lead time, and robustness against deadlock situations. It can be seen that changes in the guide path layout can have both a positive or negative influence on the number of blockings and the travel distance.

Figure 4 shows three factors of layout design that have received much attention recently and that can improve AGV-system performance without increasing number of AGVs (Hoff and Sarker, 1998):

(i) Free-path navigation. Free-path navigation is an improvement in the navigation technique of AGV-systems. It allows vehicles to travel without the presence of a physical guidepath.

(ii) Bi-directional paths. Bi-directional guide-paths increase flexibility by allowing AGVs to travel in both directions of a path at the cost of increased control complexity.

(iii) Single-loop based layout. A guide-path is divided into non-overlapping sections, or loops, with one AGV operating on each loop. The problem of a high control complexity and also blockings are solved at the cost of a higher number of load transfers and transfer stations.

Uni-directional and bi-directional paths respectively are those that operate only to the left or only to the right, and those that allow movement in both directions along the path. Control of AGVs in one direction would be simpler to manage than a bi-directional case, where guide path construction would be further confounded by the problem of a head-on-vehicle collision, the uni-directional system has been shown to be inferior to bi-directional operation, via simulation, in some aspects measured (Krishnamurthy et. al. 1993). Bi-directional guide paths have also created increased vehicle utilisation and cost savings versus a uni-directional guide path. Primarily, loop guide paths and paths defined by an objective function are used. These objectives are usually to minimise the travel distance or travel time, both relating to travel cost.

There are several approaches to the path design problem. The mathematical programming approaches are:

(i) Column generating approach: A number of researchers focused on minimising the system time for AGVs operating on bi-directional networks. This is approached by a column-generating procedure with a constrained master problem. The second type of model is a mixed 0-1 integer model used to minimise transportation, inventory, and vehicle costs (Krishnamurthy et. al., 1993).

(ii) Mixed-integer programming approach: Lagrangian relaxation is sometimes used to solve the objective function by relaxing constraints that require not all the vehicles be in the system at a given time and that multiple vehicles not be at a point on the path at the same time.

It is obvious that both of these procedures may be computationally difficult. The 0-1 integer programming model has been summarised into an algorithm to ease this difficulty. It should be noted that the integer programming model does, as a sub-objective, optimise the number of AGVs in the AGVS. While both procedures claim optimal or near-optimal solutions, no direct comparison can be made without simulation of identical problems (Krishnamurthy et. al., 1993).

(iii) Branch-and-bound approach. Sinriech and Tanchoco (1991) have evaluated the analytical approach to the guide path design question from the perspective of branch-and-bound methods. Their objectives are the same, to set directions for an undirected path so as to minimise the guide path length.

Krishnamurthy developed two heuristic approaches which both focus on guide path design optimisations through the location of the pickup and delivery stations that are part of the AGVS. Discussed here are the directional guide path and optimal loop design heuristics. Heuristic and linear programming approaches to guide path design have been shown to be effective and thorough. The heuristic approaches reviewed are both based on material flow where one is more realistic, using actual inter-departmental flow to determine optimal guide paths. The four linear programming approaches appear to be more computationally complex, though they do address additional design concerns (Krishnamurthy et. al., 1993).

Rajotia et. al. (1998b) presents another heuristic approach to the problem. This has been developed for configuring a mixed (hybrid) uni/bi-directional flow path for an AGV material handling system. The given unidirectional flow path layout , material flow intensities and vehicle travelling time matrix among various processing centres are taken as input information to this technique.

Unidirectional paths are extensively implemented since unidirectional flows reduce the possibility of vehicle blocking and are easier to control. (Egbelu and Tanchoco 1982). Bi-directional traffic patterns on the other hand require that some buffering sidings exists at the intersections of the arcs for temporary stopping of the vehicles. Most of the academic work as well as industrial applications have been done in favour of unidirectional flow design.

According to Rajotia et. al. (1998) vehicle blocking phenomenon is manifested more frequently in an AGVS consisting of bi-directional arcs, which implies an advantage for uni-directional arcs.

Seifert et. al. (1998) showed that the guidepaths of an AGV-system can be modelled as a graph consisting of nodes (or points, or vertices) connected by a set of arcs (or lines, or branches). The nodes represent locations in the system such as intersection regions or 'pickup and delivery'(P & D) stations. The arcs connecting these nodes comprise the physical or virtual guidepaths to be followed by an AGV. This graph is the primary input to the routing function of the AGV control system. Given the current location (origin node) of an AGV and its prescribed destination node, the vehicle router must select an appropriate path for the vehicle that consists of an alternating sequence of distinct nodes and arcs beginning with the origin node and ending with the destination node such that each arc is terminated by the two nodes immediately preceding and following it in the sequence. Different routes can be evaluated based on an aggregate cost of traversing the corresponding paths, such as travel distant or expected travel time.

2.2.5.1 Virtual Flow Paths

Gaskins et. al. (1989) introduces the term 'virtual flow path' to describe a system where the guide paths exist only in the system-controller software. A system with virtual flow paths is far more flexible, since the guide-path-layout software can more accurately reflect the most current material flow demands on a facility. Along with physical versus virtual, a second classification of flow paths is unidirectional versus bi-directional. Considering a virtual flow path, issues which need to be addressed include the number of lanes of vehicle flow in each aisle and the direction of flow in each lane. The best procedure may be to generate a design and then evaluate it using simulation.

In summary, guide path design ensures that parts reach their delivery points through the shortest distance possible. Uni-directional, or one-way traffic, is the most commonly used type of guide path, though bi-directional guide paths are more cost-effective (Hoff and Sarker, 1998). Path types can be loop types or a more specialised design determined by the objective of the design algorithm.

2.2.6 Dispatching of Loads and Vehicles

There are two main control policies for the control of AGV-systems, centralised and decentralised as presented in Figure 5. The more sophisticated policy is the centralised control where information about the system is used to make central decisions to avoid sub-optimisation. According to Taghaboni and Tanchoco (1988), the primary vehicle management functions for an AGV-system can be defined as:

- Dispatching, the process of selecting and assigning tasks to vehicles.
- Routing, the selection of the specific paths taken by vehicles to reach their destinations.
- Scheduling, the determination of the arrival and departure times of vehicles at certain points along their prescribed routes to ensure collision-free journeys.

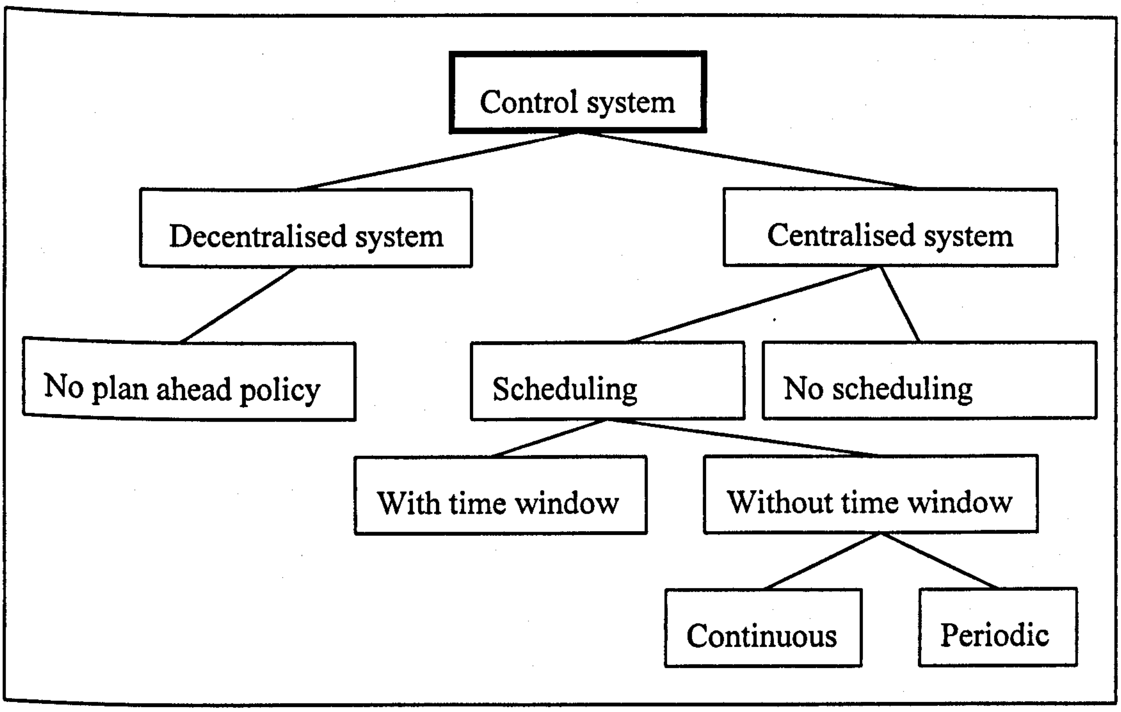

Figure 5, Operational control policies of AGV-systems. The centralised control is more complex but also more effective. Apart from scheduling, dispatching and routing are the main functions of vehicle management to handle for a control system. (Taghaboni and Tanchoco, 1988)

Taghaboni-Dutta (1997) classifies the dispatching rules used for AGVs into two classes: push and pull. The push strategy refers to dispatching rules in which the vehicle assignments are invoked by workstations that have loads waiting in their outgoing buffers. The pull strategy refers to dispatching policies that are driven by demand; that is, AGVs receive assignments based on which workstations have space in their input buffer. Although some research efforts have been directed toward decreasing the empty vehicle travel time, the time that the vehicle spends as a temporary buffer to a workstation has been generally ignored.

Hoff and Sarker (1998) provide a similar classification of dispatching rules. Push dispatching rules first choose a part to move, determines a suitable destination for that part and then chooses a vehicle for the move. This is the reverse of the pull dispatching rule where a vehicle chooses a workstation and then seeks to find a part that can be moved there based on a selection rule. Rules are also characterised as workcenter- and vehicle-initiated rules (King and Wilson, 1991). Under workcenter-initiated rules, when a workcenter has a part to be moved, it selects a vehicle from the set of idle vehicles by the chosen rule. Workcenter-initiated rules can be:

1 random vehicle;
2 nearest vehicle;
3 furthest vehicle;
4 longest idle vehicle (Chen 1996); and
5 least utilised vehicle (King and Wilson, 1991).

Dispatching or scheduling algorithms have several assumptions that they are based on, including at what time in the system cycle decisions will be made about assigning pickup and delivery moves to given vehicles.

Lee, et. al. (1996) examined the operation of multiple-load AGVs in a flexible manufacturing system where AGVs in the system are capable of carrying two or more loads. The load selection problem arises when an AGV stops at a pick-up queue and has to decide which part(s) should be picked up. Five heuristic rules that may be used to select the load to be carried were suggested and evaluated under a hypothetical flexible manufacturing system with the aid of computer simulation. The results revealed that the variable-route-part-priority (VP) rule and fixed-route-part-priority (FP) rule generated significantly higher throughput then their counterparts, while the 'pick-all-send-nearest'(PN) rule outperformed the other rules in part flowtime and work-in-process level. The results also suggest that when the carrying capacity of the AGV increases, the performance differences among the rules also increase. This finding sustains the need to explore an efficient operation strategy of multiple-load AGVs in flexible manufacturing systems.

Shen and Lau (1997) states that in order to minimise the waiting time for the material, the next section gives a two-phase model, which takes into account the required number of vehicles to meet a specified maximum level of probability (α) that the system has more load request than the number of vehicles at any arbitrary point in time. Under these situations, the AGVS will remain in the workcenter-initiated situation most of the time so that the load requests will have the shortest waiting time.

in this guide path layout design, an AGVS network is modelled as a graph consisting of nodes connected by a set of arcs. The nodes represent points on the network, such as pickup and/or delivery stations and intersections. At these nodes, the next immediate segment in the path is selected by an AGV traversing a route. The arcs represent the virtual guide paths in which vehicles travel from node to node. Associated with each arc is cost which denotes either the distance between the two end points of the segment, or the time required by an AGV to cross the arc.

Malmborg proposes a framework where the system designer can interactively screen preliminary design solutions prior to the development of the simulation models used to develop and validate design specifications. This makes it possible to explore a broader range of the design solution space in a process of intelligent enumeration. Unfortunately, analytical models for AGVS design reported in most previous literature fail to capture more than one or two of the basic criteria influencing the effectiveness of a system design. An analytical model has been designed to accommodate the full set of major decision variables involved in the design of zone control AGVS (Malmborg 1991).

2.2.7 Routing

Routing is the process of selecting the specific paths taken by vehicles to reach their destinations. Taghaboni-Dutta (1997) proposes two routing strategies, i) source-to-goal routing and ii) node-to-node routing. Simulation experiments where conducted to compare these and the results show that node-to-node routing generally has a poor performance due to the difficulties in obtaining accurate estimates of the traffic conditions and the lack of global look-ahead capability. In the latter case it is implied that rerouting can be made.

According to Seifert et. al. (1998) the evaluation of alternative routes and the actual routing of a vehicle can be either static or dynamic:

- Static routing: the path taken by an AGV between any two given nodes is always the same, the route does not vary over time as a function of the current congestion in the system. The most natural solution is always to select the path with the shortest travel distance.
- Dynamic routing: different paths can be taken by an AGV at different times when moving between two given nodes. Taking into consideration the current status of the system, the vehicle router selects a path for the AGV at the time that the vehicle is dispatched and if there is a communications link between the router and the vehicle, then the router modifies the vehicle's path during travel.

Narasimhan, et. al. (1999) criticises the approach of pre-planning since they assume no interruptions en route. For a completely automated plant, these methods are applicable. However, for factories in which both humans and AGVs work alongside each other, interruptions are commonplace and need to be addressed. A few situations that lead to interruptions are:

- An AGV malfunction (dead batteries or vehicle breakdowns).
- Objects blocking an AGV path, causing delays.
- Manual intervention (human operators shutting AGVs off).

Discussions on AGV interruptions have not been found in the literature - ideal operating conditions are assumed when devising AGV routing and scheduling approaches.

2.2.8 Dynamic Routing and Scheduling

Dynamic routing implies that the route is not fixed, but can be changed during the travel to accommodate changes in the circumstances. Many researchers have used the technique of computer simulation to address the problem of dynamic vehicle routing. The main motivation is that using a simulation model provides a system-wide view of the effect of a local change in the AGV-system. In the following discussion, two successful approaches are explained.

Taghaboni and Tanchoco (1988) developed a LISP-based controller for free-ranging AGV-systems. In the first phase the authors performed a simulation-based performance evaluation of a job shop, where transportation was critical. It was shown that increasing the number of vehicles improved the throughput of the system up to a point; and beyond that point the throughput started to decrease. This decrease was due to vehicle blocking, that is self-congestion, causing unit loads to spend more time on vehicles travelling to workstations. In the second phase of their work the authors developed an intelligent supervisory controller. This was designed for dynamic vehicle routing to address the problem of vehicle blockage at intersections. Initially, the best route is assumed to be the one that results in a minimum travel distance. The vehicle controller then provides a timetable of occupation times for each node along the vehicle's route. The times for the new journey are compared with the previously schedule journey times, and thereby conflicts are identified between the new route and the nodes′ reserved occupation times for all the other journeys. If a conflict is detected, then the conflict resolver will explore alternate routes with the objective of finding a route that will minimise delay time. The objective is realised either by slowing down the vehicle on a certain route or by selecting an alternative route without conflicts.

Kim and Tanchoco (1993) present an efficient algorithm for finding conflict-free shortest-time routes for vehicles in a bi-directional AGV-system. The algorithm is based on the Dijksra′s shortest-path method. To prevent the collision of vehicles, it introduces a time window graph in which the node set represents the free time windows and the arc set represents the reachability between free time windows. The algorithm then routes vehicles through the free time windows of the time window graph.

Oboth et. al. (1999) presented a large-scale simulation of a job-shop to test the feasibility of the scheme for real control of AGVs and to determine the effect of several factors on several performance measures. The findings indicate that performance is significantly affected by vehicle speed, number of vehicle, demand arrival interval, idle AGV positioning, and the dispatching policy in use. The authors strategy assumes the existence of a set of demands, each consisting of a pickup and delivery. The intention is to transport all these demands in a manner that minimises the makespan, the time when all demand deliveries have been made, and at the same time avoids AGV collisions.

Krishnamurthy et al. (1993) developed a static version of the AGV routing problem. That version dealt with the problem of routing K AGVs in a network to satisfy their request while avoiding conflicts and minimising the performance measure of makespan, the maximum time taken to satisfy all the demand requests. The system time drops as: the number of AGVs is increased. The speed of the AGVs is increased, and the demand arrival interval increases.

According to Ho (2000) strategies in the scheduling category predetermine the route plan for each vehicle or implement a real-time control on each vehicle to prevent the collision of vehicles. These strategies determine the exact routes of vehicles under an assumption that all transport requests can be known ahead. However, solutions found by these strategies are difficult to implement in a real-time manner because of their less realistic assumptions and computational complexity.

2.2.9 Vehicle Management and Operational Control

The management of vehicles at an operational level includes dispatching of transport tasks and vehicles, routing, scheduling and planing ahead, and traffic management. Using the information of transport requests, status and position of vehicles, the central controller should decrease empty travel time while avoiding blocking and dead-locks. This should result in a high throughput with a low number of AGVs. As mentioned in the guide-path design section, the dispatching strategy interrelates with the guide-path design and both must be considered to result in a good AGV-design.

One traditional vehicle-collision prevention strategy is the zone strategy that divides guide paths into several non-overlapping zones, and restricts the presence of vehicles to at the most one at any time. Another type of zone-blocking is the tandem guide path configuration in which every zone is served by one AGV and the guide path of each zone is a single loop.

Mantel and Landeweerd (1995) use a somewhat different approach in order to decide on the interaction between the operational control of the transportation system and the operational control of the production system. Production and transportation can be controlled separately (e.g. schedule production tasks first and, taking the resulting time scheme as a starting point, subsequently schedule the transportation tasks required) or to integrate both control activities. The interaction between production and transportation control seems to attract little attention in the literature, most authors assume a certain arrival pattern for transportation tasks and restrict themselves to the control of the transportation system.

The transportation control is either centralised or decentralised. A centralised control implies that all transportation tasks are concurrently considered and then the vehicles are routed and scheduled to perform them. In contrast, the First encountered First Served (FEFS) rule (i.e. a vehicle makes a tour and performs the first transportation task ii encounters, in other words an AGV looks for work) is a decentralised way of control, that is typically suited for a single-loop and a tandem configuration. Task assignment means that one of the tasks on a list, according to a certain priority, is assigned to a vehicle that becomes idle. Idle vehicle assignment means that one of the vehicles from a set, according to a certain priority, is assigned to a task that arrives. A transportation task assignment rule can be either a push or a pull type rule, where respectively the output buffer of a station controls the priority of a transportation task. In fact, a pull rule implies an integrated control of production and transportation.

Two situations can be distinguished: (a) think-ahead control without time windows. (b) think-ahead control with time windows. So time plays a crucial role here; not only routing is involved, but also scheduling. Given such a production schedule and the loaded trips (transportation tasks) due to the product routing, all feasible empty trips can be determined. The transportation lead time for both a loaded and an empty trip consists of transportation and waiting time. If there is no feasible solution, then the production schedule must be adapted. How to handle that is still an open question. The resulting transportation schedule is maintained and executed until a production schedule demands to make a revised one. Not only the arrival rate of transportation tasks but also the length of the time horizon determines the nervousness of this way of control. A possible approach for integrated control of single-load vehicles is the following. By modelling an AGV-system as a set of parallel machines, with processing times equal to transportation times and by modelling empty travel times as change over times, it could be possible to use a shop floor scheduling of production and transportation (Mantel and Landeweerd 1995).

So far operational AGV control policies are discussed, which constitute the upper hierarchical level of operational control. As stated before, this level controls the assignment of transportation tasks to vehicles. Knowing the assignment, it is possible to reduce the routing and time schedule for each AGV. Then, given the track layout, one may predict where the AGVs interfere with each other, which results in congestion. The lower level of control, the traffic control, has an effect to the amount of congestion. If this is too high, it may be tried to find blocking-free routes by rerouting the AGVs. Generally, this will lead to a revised task assignment. One of the advantages of creating blocking-free routes is that the travel time variances are reduced, so that the routing optimisation problem gets a more deterministic character.

Most probably, an integrated control of production and transportation with "think-ahead" will yield the best system performance. Probably the basic concept, a much more simple approach to be discussed next, in which production and transportation are coordinated to a certain extent, will also produce good result. When a product enters an output buffer of a station, centrally it is added to a list of transportation tasks to be performed. As soon as an idle vehicle becomes available, then the first transportation task on the list is assigned to that vehicle, provided that there is enough space in the input buffer of the destination and if, looking at the production schedule, the product involved is shortly to be processed at the next station. If transportation takes place by means of AGVs, then the lead times are harder to predict, so that a pull policy implies that items will often arrive too late (Mantel and Landeweerd 1995).

Liu and Hung (2001) presented an unmanned automated job shop manufacturing system with a single multi-load automated guided vehicle, which traverses around a single-loop guidepath, is considered in this work. This type of job design is often used as an independent sector of some complex AGV layouts, such as tandem, segment bi-directional single-loop and divided configurations. The type of multi-load vehicle is a good alternative against using more single-load vehicles to serve a higher transportation demand. To an unmanned automated manufacturing system, the management of finite system resources, e.g. finite input/output queuing space and transporting carriers, plays a vital role in avoiding system deadlocks and machine blockages. The proposed control strategy for a single multi-load vehicle uses global shop real-time information to achieve the objectives: avoid shop deadlocks causes by inappropriate job movement as well as satisfy the system transport requirement. The efficiency of the proposed vehicle control strategy and the other two expanded strategies under various parameter designs are verified by computer simulation.

2.2.10 Deadlocks in AGV Systems

An important issue in the operational control of a manufacturing system is the handling of system deadlocks. This can be a logical state of an automatic system which is impossible to resolve without manual intervention, or an AGV which has traversed off its guide-path blocking the other AGVs.

Modern manufacturing philosophies, e. g. lean manufacturing, often dictates the removal of waste and lean operation of production systems. This implies that in the case of AGV-systems as little resources as possible are utilised while retaining a required level of service. The intermediate buffer levels and work-in-process is also kept low. A production system with few intermediate buffers between operations is sensitive to interruptions in the flow of material. A well balanced AGV-system is under these circumstances of high importance. The consequence of frequent deadlocks in the MHS can be devastating for production throughput. Consequently, a well-designed AGV-system should prevent and if possible resolve deadlocks.

In the literature deadlocks are considered to be the logical state of an AGV-system, still similar problems will occur if an AGV loses its position, orientation or guidewire. This is described in more detail in section 2.3.3, in the following section, the logical state of a manufacturing system is considered.

Deadlocks can occur when some resources are shared by several processes and a process holds a resource while waiting for another resource to become available. If a circular wait occurs, with a closed chain of processes all waiting for a resource held by the next process, then the system is in a state of deadlock. Figure 6 to 9 shows deadlocks in AGV-systems at various levels of system control (Kim et. al. 1997).

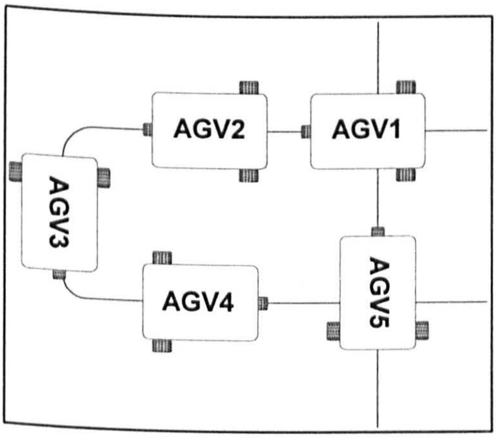

Figure 6. Vehicles blocking each other at intersection. All vehicles are waiting blocked by other vehicles that have stopped at intersections. This is caused by careless AGV traffic control.

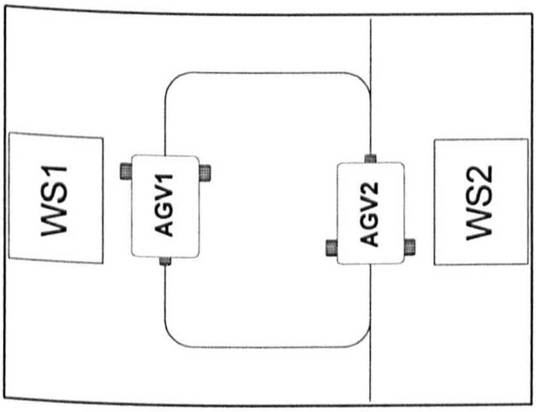

Figure 7, Deadlock caused by careless AGV path planning. AGV1 at workstation 1 (WS1) is routed to workstation 2 but is blocked by AGV2. AGV2 is routed to workstation 1 but is blocked by AGV1.

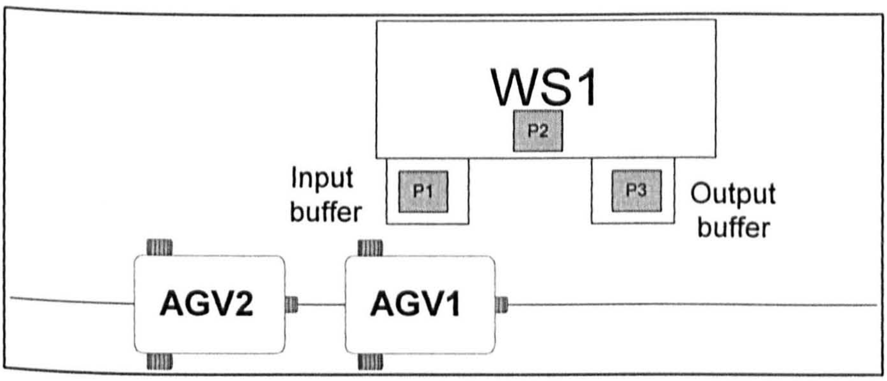

Figure 8, Deadlock caused by careless AGV dispatching. The job P2 on the machine cannot be unloaded because of the full output buffer, and thus is blocking further operation of the machine. AGV1 is waiting to unload at the full input buffer AGV2 routed to the output buffer is blocked by AGV1.

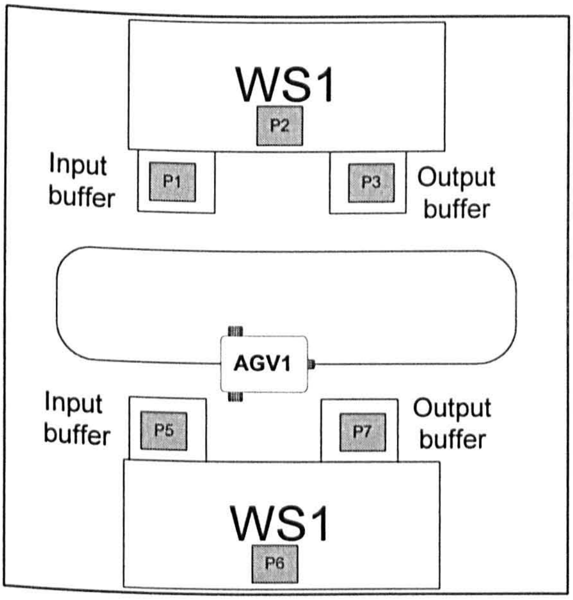

Figure 9, Deadlock caused by careless material flow control. Part 3 is waiting to be transferred to workstation 2 which is busy processing part 6 and whose input buffer is occupied by part 5. Part 7 is waiting to be transferred to workstation 1 which is busy processing part 2 and whose input buffer is occupied by part 1.

The strategies for handling system deadlocks can be classified into

(i) **Deadlock prevention without look-ahead**, statically establish dead-lock free operation ensuring that the necessary conditions for dead-locks cannot be simultaneously satisfied.

(ii) **Deadlock prevention with look-ahead,** dynamically allocate system resources by using an online control policy

(iii) **Deadlock detection and recovery,** allow deadlock to occur, then use mechanisms to detect and recover it. (Kim et. al. 1997, Liu and Hung 2001)

According to Liu and Hung the deadlock detection and recovery approach is overly optimistic. In addition, although the prevention and avoidance approaches often excessively restrict the use of resources and even penalise the system performance measures, they are more practical in reality. The avoidance method is normally more flexible than the prevention method. For instance, the Banker's algorithm tries to prevent deadlock (Kim et. al. 1997). The basic idea of this algorithm is that all possible future request for resources can be satisfied with the current set of free resources at any time. However, the algorithm does not consider the order in which resources would be requested. It might prohibit free resources from being allocated to waiting jobs whenever the total future demand for the resources by active jobs equals the resources capacity.

2.3 Design of Automated Guided Vehicles

Autonomous Guided Vehicle design can include many phases of engineering: mechanical design, electrical design, problem analysis, establishing requirements, programming of AGV-controller, choice of control architecture and navigation techniques and sensors etc..

This section does not include details in mechanical and electrical engineering since these aspects are outside the boundary of simulation in the context of this thesis. Mechanical and electrical design can take place in parallel with simulation studies in a concurrent engineering context.

It appears to be a common understanding in the reported research about AGV-system design that there is a large potential in:

(i) use of bi-directional paths, if an appropriate transport control is achieved,

(ii) use of multi-load vehicles as this can considerably decrease required number of AGVs and increase maximum throughput,

(iii) use of free-path vehicles to increase flexibility, if this can be motivated. (Bilge and Tanchoco 1997, Hoff and Sarker 1998)

A literature review summary is presented in Appendix 1.

AGV-systems are increasingly becoming more flexible and the vehicles become more autonomous with improved functionality in terms of navigation, load-handling, and control architecture of AGV-system. A novel development is the Semi-autonomous vehicle (SAV) concept which is a module-based vehicle with multiple sensor systems. The SAV is described in detail in section 1.3.4.

2.3.1 Wheel Configuration and Kinematic model of an AGV

For wheeled vehicles there are a number of configurations. Some of the most commonly used are i) differential steering, ii) ackerman steering iii) synchro drive and, iv) tricycle drive.

Differential steering is common in laboratory applications, see Figure 10, but suffer from low load capacity, by design unstable steering (difficult to achieve straight line motion, higher speed etc.) and have very few applications in industry. Synchro drive has similar problems as differential steering.

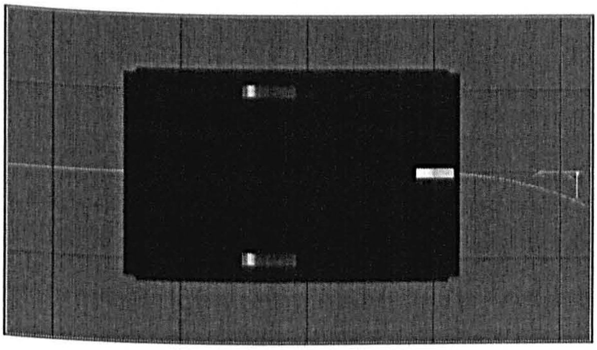

Figure 10, Differential steering. A three wheel configuration with two independent driving wheel and one free-castoring rear wheel.

In automotive industry Ackerman steering is used almost exclusively. It is designed to ensure that the inside front wheel is rotated to a slightly sharper angle than the outside wheel when turning, thereby eliminating geometrically induced tire slippage. The extended axes of the front wheels intersect in a common point the extended axis of the rear axle. This geometry is said to satisfy the Ackerman equation (Everett 1995).

$$\cot\alpha_i - \cot\alpha_o = \frac{d}{l}$$

where

α = *relative steering angle of inner wheel*
α_o = *relative steering angle of outer wheel*
l = *longitudinal wheel separation*
d = *lateral wheel separation*

An imaginary wheel in between the two front wheels (in comparison with a tricycle drive configuration), having a steer angle of α_c, can be expressed in terms of either the inside or outside wheel.

$$\cot\alpha_c = \frac{d}{2l} + \cot\alpha_i$$

or

$$\cot\alpha_c = \cot\alpha_o - \frac{d}{2l}$$

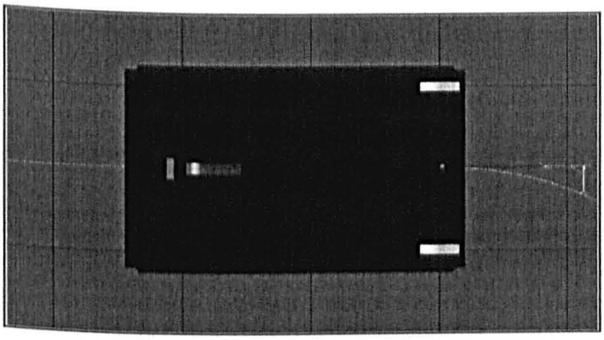

Figure 11, Tricycle drive configuration. The front wheel to the left is driving and steering, with two passive wheels at the rear.

The tricycle drive configuration with a single driven front wheel and two passive rear wheel are very common in AGV applications, see Figure 11. The odometry solution in the form of steering angle encoder is equivalent to that of ackerman steering. Also rear-axle differential odometry can be used to determine heading.

One commonly used kinematic model of AGVs is the bicycle model showed in Figure 12 (Nelson and Cox 1990, Weiczer 1995). In this model of a vehicle an instantaneous radius of curvature r, and a velocity, v is used. The two degrees of freedom, the steering angle and the angular velocity of the drive wheel can be obtained as:

$$\phi = \arctan\frac{l}{r}$$

$$\omega_h = k_d \frac{v}{r_w}$$

where ϕ is the steering angle, ω_h is angular velocity, l the wheelbase, and r_w the drive wheel radius and k_d the gear ratio.

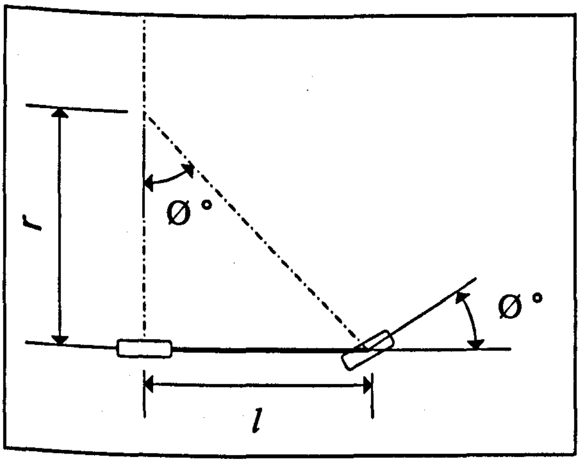

Figure 12. Bicycle model of a vehicle.

Assuming a zero steer angle as a nominal point, a linear gain can be used to relate the steering motor angle to a hypothetical steering angle, ϕ_h.

$$\phi_s = k_s \cdot \phi_h$$

k_s can be obtained from the ratio of the covariance and the variance of (ϕ_h, ϕ_s) obtained form experimental data.

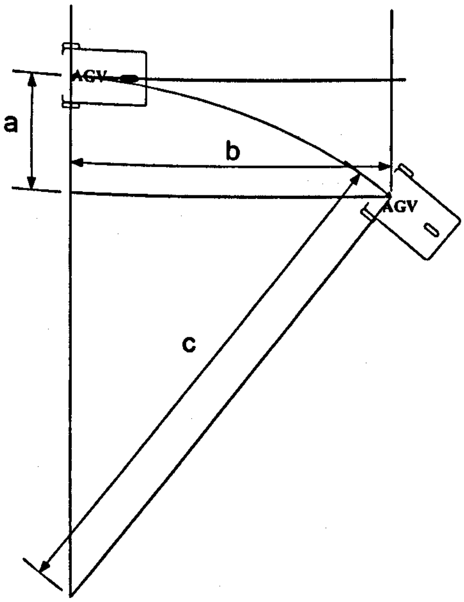

Figure 13. Radius of curvature.

To calculate the turn radius *c*, given the distances *a* and *b*, the formula is:

$$(c-a)^2 + b^2 = c^2$$

which gives:

$$c = \frac{b^2 + a^2}{2a}$$

See Figure 13.

This simple linear model will be used for the control level of the vehicle model and deficiencies in repeatability and accuracy are left to be compensated for by higher levels of control.

2.3.2 Dynamic model of an AGV

In the control of mobile robots it is common to establish the basic kinematic relationships, but to place less emphasis on modelling the dynamics. Shin and Singh . (1990) have identified two reasons for modelling the dynamics of a vehicle: i) vehicle actuators have less than perfect response, with better models the chance of compensating these effects is better, ii) a good model of the vehicle is required for simulation to test and improve algorithms. The dynamics can be divided into two phenomena, actuator dynamics and vehicle ground interaction.

The vehicle-ground interaction (VGI) is a description of the vehicle motion for a given steer angle, wheel angular speed, vehicle mass, friction between the road and wheels, and in the case of outdoor vehicles, typically tire stiffness and other variables. For AGVs however, the latter is of little importance, as the wheels can in most applications be considered stiff. In general, VGI is a very complex problem and cannot easily be modelled. One solution is to avoid explicit representation of wheel slip for trajectory evaluations as proposed by Graettinger and Krogh (1989). They assumed there is a bounded region of operation within which the slip is negligible. The system must then operate within the assumed constraints by speed adjustment to stay within no-slip bounds. An upper limit of speed can be acquired for which the vehicle will not slip, and thus reducing the control problem to a kinematic one. In the following work the approach of Graettinger and Krogh will be followed, thus modelling the dynamics of the vehicle but not the VGI.

A block diagram of a steering and drive system is shown in Figure 14. It consists of two DC-motors and programmable drive and steering controllers containing the whole servo loop. The drive controller acceleration rate (time to reach 100% output from 0% output) and deceleration rate can be set between 0.2 and 3.0 seconds. This controller is used in the Euromation AGV, see section 2.3.4.

Shin and Singh (1990) suggests that the types of drive and steer train can be sufficiently modelled as first order systems with a time constant, especially in the case of steering. Such a prediction of ϕ_h for the steering system can be made as:

$$\phi_h(t) = \frac{\phi_s}{k_s}(1 - e^{-t/\alpha})$$

For smaller angles this should be sufficient, while for larger signals hard limits may have to be imposed.

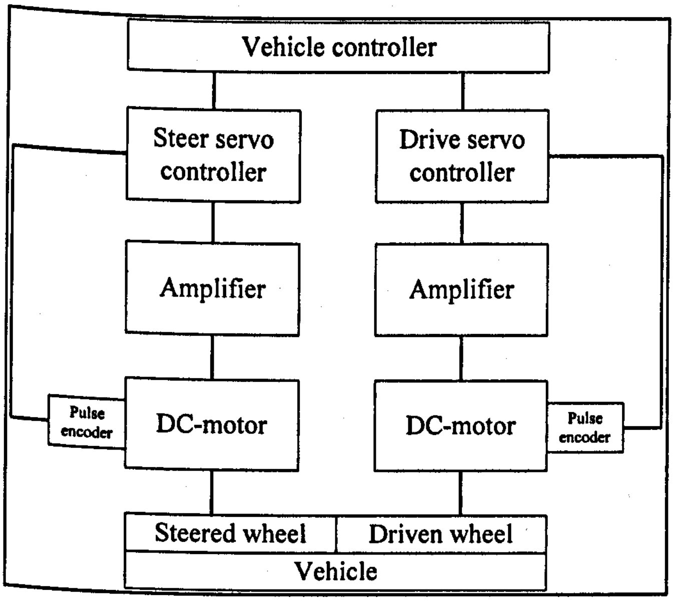

Figure 14, Drive and steering system of a vehicle. Example taken from a Semi-autonomous vehicle developed by Euromation (Moore et. al. 1998).

2.3.3 Sensors and Navigation Techniques

The most common navigation techniques used in AGV-systems are presented together with novel approaches which are mostly used in mobile robots research. The novel techniques are however increasingly moving in to manufacturing environments. According to Arkin and Murphy (1990) the AGV-systems that are currently dominating Flexible Manufacturing systems generally require significant restructuring of the workplace in order for them to be useful. This is the opposite of a major navigation philosophy in mobile robot research where a fundamental idea is adaptivity. Brooks states that 'the world is its own best model' as a motivation for behavioural control architecture instead of the functional architectures that are traditionally used in e. g. AGV-systems, see Figures 15 and 16 (Brooks, 1986).

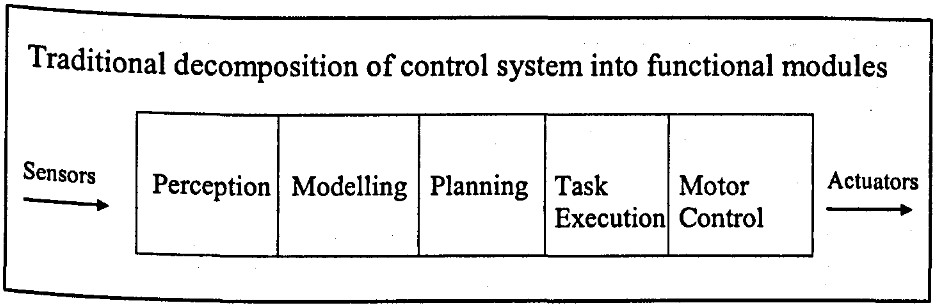

Figure 15, Functional Control Architecture. The traditional decomposition of tasks for a mobile robot according to Brooks (1986).

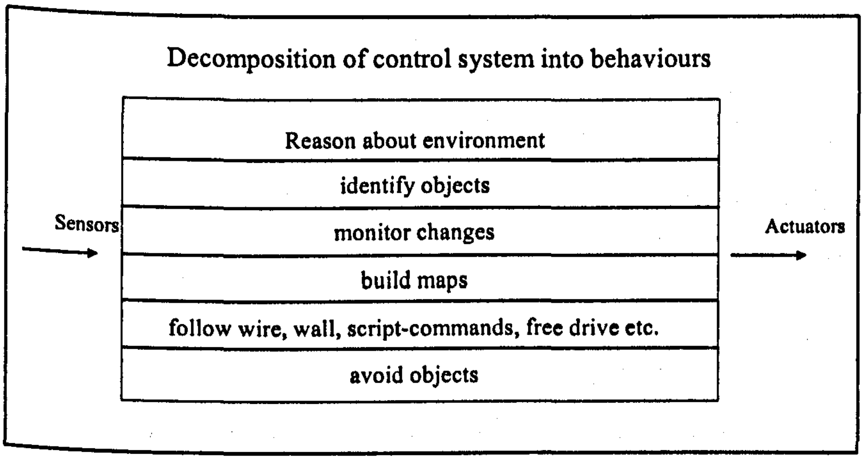

Figure 16, Behavioural Control Architecture. Tasks are executed in parallel instead of a in a hierarchical order (Brooks 1986).

This approach, which is contrary to the AGV methodology, embeds significant amounts of knowledge, both environmental and behavioural, to ultimately give a mobile robot far greater latitude in interacting with its environment.

The process of perception is based on navigation. In Figure 17 a hierarchy of navigation techniques that can be used by AGVs is presented.

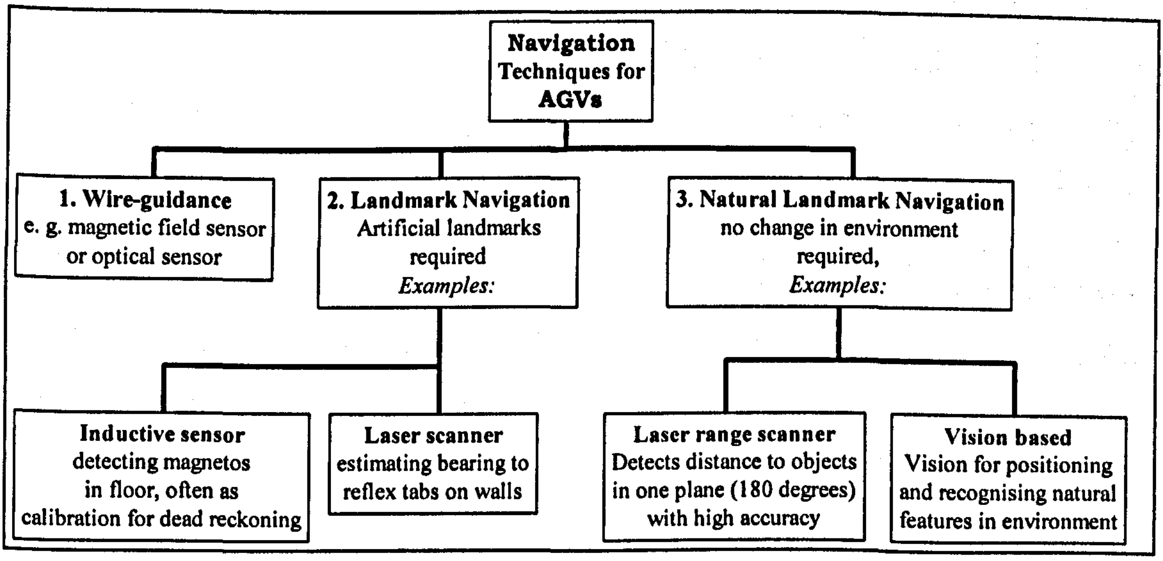

Figure 17. Navigation techniques for AGVs. Wire-guidance is the traditional technique in AGV-systems. Landmark navigation and especially the use of laser scanners is becoming commonplace e. g. a system developed by NDC (2000). Natural landmark navigation as the main technique is rarely used in industrial applications and robust commercial systems remains to be developed. Examples of local feature recognition exists (Moore 1999) e. g. automatic pallet loading.

However, the nature of a manufacturing environment with precise production schedules requires a very predictable behaviour of the material handling system. Existing approaches used by AGV's place severe restrictions on the ability of the vehicle to interact with the workplace. In many instances, it cannot leave a predefined track nor cope with any unexpected obstacles in its way other than to wait for them to be removed. Furthermore, significant restructuring of the workplace is often required for AGV's to be useful. Navigation techniques must also be very robust against all types of disturbances (wear of optical stripes on floor, polluted air blocking laser beams, etc.). This has left little room for novel landmark based techniques, if the failure rate is above an absolute minimum the AGVs can easily cause chaos in the workshop. A motivation for the popularity of wire-guidance is its reliability although very inflexible to layout changes. While AGV-systems are more and more designed with landmark based navigation systems the mobile robot community are embracing ideas of developing robust natural landmark navigation. This seems to be ideal not to change the environment instead having the MHS-equipment to adapt.

According to Mellado et. al. (1999) AGV-system performance requires innovations in areas such as real time features for scheduling, path planning and status monitoring as well as health monitoring, sensor data fusion, including Fuzzy Logic and occupancy grid processing schemes, to derive robust, low cost ranging systems for navigation and obstacle avoidance purposes.

The use of sensors is vital for the operation of an AGV or a mobile robot. Sensors are the only channel to receive information about the environment of a vehicle. Design considerations arise directly from the inherent need to interact with physical objects in the environment. The vehicle must be able to navigate from a position to a desired new location and orientation, avoiding any contact with any objects during travel. There is a need for developing collision avoidance and navigational technologies along with the technological development (Everett 1995). Fundamental in this regard are the required sensors with which to acquire high -resolution data describing the robot's surroundings in a timely yet practical fashion, and in keeping with the limited onboard energy and computational resources of a mobile robot. In the following general design consideration for sensors, the application and task at hand is, as obvious, critical for what parameters should be used. Some general considerations for this type of sensors as stated by Everett are:

- Field of view, wide enough with sufficient depth for the application
- Range capability, minimum and maximum range of detection for intended use of sensor
- Accuracy and resolution
- Ability to detect all objects in environment (if necessary for application), e. g. absorbing and diffuse reflector objects
- Real-time operation, update frequency must comply with the vehicle speed (also approaching vehicles)
- Concise and easy to interpret data, output format should comply with processing capacity, enough amount of data, if output is needed only when action is required some degree of pre-processing and analysis is required

- Redundancy, provide graceful degradation and not become incapacitated at the loss of sensing elements
- Simplicity, the system should be low-cost and modular and not hardware specific, to support easy maintenance, and. Upgrades
- Power consumption, power requirements should be minimal due to limited resources
- Size, practical physical size and weight with regard to intended vehicle

A sensor in its simplest form may provide information one-way, regardless of the situation of the vehicle and task, while at a more sophisticated level, some sensor data pre-processing and analysis is made, and output is only provided on request, from the vehicle or triggered by a, from the vehicle's perspective, external event. The sensor can also be controlled e. g. which area to focus on, what update rate, and what mode of function.

2.3.3.1 Landmark based Laser Scanner

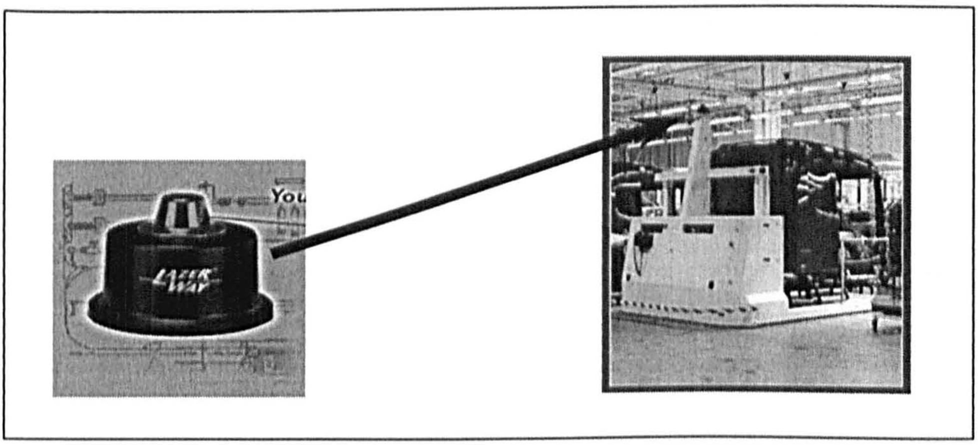

Figure 18, The Laserway laser scanner. This is a landmark based system where the rotating head to the left is placed so that a free line of sight is possible to at least three reflecting tabs which are positioned in the AGVs environment (NDC 2000). The laser scanner, in difference to laser range scanners, only measures the angle to the tabs and calculates its position via triangulation and integration of previous positions.

A common AGV navigation application, which is taking over from wire-guidance is landmark based laser scanner systems. They provide similar benefits of robustness and reliability, but are much more flexible for changing the path layout.

One commercially available product is shown in figure 18 (NDC 2000). Programming is done by a ‘teach-in’ function. The AGV is, using manual controls moved along its path and the laser scanner records the position of the landmarks as an internal map. The disadvantages of this system are: i) potentially less accurate position for the vehicle due to parallax errors if the scanner is placed in a high position, ii) reflecting shining surfaces, e. g. stainless steel equipment common in food processing, can cause unwanted reflections, iii) the positioning of reflecting tabs and the free-line of sight can be difficult to maintain in cluttered environments.

2.3.3.2 Natural Landmark based Laser Range Scanner

An LRS is a navigation sensor that can use natural features in its environment for navigation purposes. If features such as walls and doorways can be reliably recognized, navigation commands could be used that resembles the human way of navigating, e. g. referencing the third door to the left, follow the corridor and then go to the second door to the right etc.. This requires behaviors as wall-following, door-way recognition etc..

An LRS measures the distance to objects using time-of-flight calculation of laser-beams reflecting on objects. These measurements can be made in either one or several directions with a high accuracy (Ujvari and Moore 1998). An example of a commercially available LRS is the SICK PLS (SICK 2002). This detects objects by sweeping a plane of 180 degrees up to a distance of 80 meters, see Figure 19. The accuracy is +\- 1 cm. This sensor is described in more detail in section 6.2.1.

Figure 19, The LRS SICK PLS.

2.3.3.3 *Dead reckoning*

Dead reckoning comes from deduced reckoning, which is a simple mathematical procedure for determining the present location of vessel by some previous position through known course and velocity information over a given length of time (Everett 1995). Both directional and velocity information is included in the term dead reckoning. In terms of control, the procedure is an open system.

One simple implementation of this method is sometimes named odometry, to measure the travelled distance, often by counting wheel rotations. The vehicle displacement along path of travel is directly derived from an odometer. Heading information can be indirectly derived from on-board steering angle sensor, supplied by a gyro or similar, or calculated from differential odometry. For straight line motion, updates to the vehicles position are given by:

$$x_{n+1} = x_n + D\sin\Theta$$
$$y_{n+1} = y_n + D\cos\Theta$$

where D = vehicle displacement along path, Θ = vehicle heading

There exist a number of sensor for velocity and angular displacement sensors:

- Brush encoders
- Potentiometers
- Synchros
- Resolvers
- Optical encoders
- Magnetic encoders
- Inductive encoders
- Capacitive encoders

The three most common are i) potentiometers, ii) resolvers, iii) optical encoders.

Synchros and resolvers are electromechanical rotating devices used to transmit angular information with high precision.

2.3.3.4 Doppler and inertial navigation

To reduce the effects of errors as wheel slippage of rotational displacement sensors, doppler and inertial sensors can be used (Everett 1995). Actual ground speed Va can be derived from the measured velocity Vd by:

$$V_A = \frac{V_D}{\cos\alpha} = \frac{cF_D}{2F_O \cos\alpha}$$

where

$V_A = \textit{Actual ground speed}$
$V_D = \textit{Measured doppler speed}$
$\alpha = \textit{Angle of declination}$
$c = \textit{Speed of light}$
$F_D = \textit{Observed doppler shift}$
$F_O = \textit{Transmitted frequency}$

There exists off-the shelf ultra sonic low-cost units (by Nike, called the Nike Monitor) designed to be worn by runners and skiers with an error of within 10 feet on a mile (gives approx. 0.5% error).

To achieve a close to optimal dead reckoning system, sensor fusion of rotary displacement sensors, an ultra-sonic doppler sensor, and an inertial sensor should be sufficient to most applications.

2.3.3.5 Inertial navigation

Initially developed for aircraft, but used in missiles, space maritime as nuclear submarines (Everett 1995). Operates by continuos sensing of minute acceleration in each of the three directional axes, and integrate over time to derive velocity and position. In other words measures not rotational but translational accelerations, while the sensor platform is stabilised gyroscopically to maintain consistent orientation of the three accelerometers. A high quality internal navigation system cost considerably much ($50 000).

2.3.3.6 Gyroscopes

There are basically two types of gyros, mechanical and optical. Optical sensors have developed during three decades, and have a wide dynamic range, highly linear, and very low projected cost. Two basic types of *rotation sensing* gyros are i) rate gyros, providing a signal proportional to the turning rate, and ii) rate integrating gyros, indicating actual turn angle or heading. The latter can in comparison with magnetic compasses only measure relatively and must be initially referenced to a known orientation (Everett 1995).

Mechanical gyros operate on the basis of conservation of momentum, where the fly-wheel gyro is the most common.

The first practical optical gyro is a ring laser gyro developed by Macek. It was introduced in the navigational systems for Boeing planes in the 1980's. Many car applications utilises fiber-optic gyros. Advances in technology makes gyros one of the most promising sensors for mobile robots.

2.3.3.7 Natural landmark referencing

There are two approaches to mobile robot perception and architectures, namely reactive architectures and functionally based architectures. One of the differences is the use of world models, common in functionally based systems. From another aspect, what should be the reference co-ordinate system, the vehicle itself or an absolute reference to the environment? With the reference co-ordinate system on the vehicle, input via the sensors is the main information source for perception, not also world model fitting.

The concept of natural landmarks is appealing, in that the environment need not be changed. The passing of doorways can, for the robot present a possibility to obtain an accurate position update, which would be an elegant solution to cumulative dead-reckoning errors.

2.3.3.7.1 Wall referencing

Wall referencing is most commonly used to derive position and orientation information. The performance is primarily determined by accuracy limitations of the measurement techniques used. There are four existing methodologies, i) tactile, direct physical contact with wall of known location and orientation, ii) non-contact static, from a stationary position determining offset and orientation from non-contact range data, iii) non-contact dynamic, the vehicle derives offset and heading from continuous real-time range data while in motion, iv) some combination of i to iii. The dynamic approach can be used to derive virtual path instructions, e.g. wall approaching or wall-following. The Cybermotion Navmaster and TRC Helpmate (Cybermotion 2002) mobile robots both rely on wall-following techniques. The wall is used for obtaining a navigational reference rather than being a part in a servo-controlled technique. A virtual path derived from a wall will inherently include the inaccuracies of sensors and the line-fitting algorithm, and not be as stable as e. g. a physical wire-path.

Wall following can effectively be used to reset the robots heading and lateral position coordinate, but not displacement along the path of travel. To achieve a complete navigational update (position and orientation), a corner can theoretically serve as reference, which should work fine for e.g. laser range scanners, but in the case of ultrasonic transducers problems occur due to specular reflections and beam divergence.

Wall following is typically used where a vehicle travels in parallel to a wall with a specified lateral separation.

For a number of measurements of the lateral separation, a straight-line fit can be made to the data points using linear regression techniques. For results that fulfil predetermined requirements, the line can be used to calculate lateral offset and current heading of the vehicle with reference to the wall. The linear regression equations to achieve slope, intercept, and estimated variance can be:

$$m = \frac{n\sum(x_i y_i) - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2} \qquad Y_I = \frac{\sum y_i - m\sum x_i}{n}$$

$$\sigma^2 = \frac{\sum y_i^2 - Y_I \sum y_i - m\sum(x_i y_i)}{n-2}$$

where:

m = slope

n = number of distance readings taken

σ^2 = variance

Y_I = intercept

The equation takes the form of $y = mx + Y_I$. By calculating the arctangent of the slope, the vehicles heading is obtained: $\Theta = \arctan(m)$

2.3.3.7.2 Doorway referencing

In some in-door environments, the robot must travel through doorways, and this manouvre can be used for a positional update, e.g. solve the problem of cumulative dead-reckoning errors. It could also serve as one component for a descriptive map using vague motion/navigation commands. The doorway entering approach for the mobile robot ROBART II (Everett, 1995) can be decomposed into these tasks: i) finding doorway, ii) entering doorway, iii) verifying doorway, iv) determining longitudinal position relative to doorway, v) determining lateral position relative to doorway, vi) determining heading relative to doorway. ROBART II makes use of ultrasonic ranging sensors with good distance but poor angular resolution, and optical proximity sensors with the opposite features. The task of finding the doorway is simplified by a priori information from a map structure about the location of the door.

2.3.4 Semi-Autonomous Vehicles

There is a group of vehicles used in materials handling, mainly in industry, that have a fundamentally different task objective than autonomous mobile robots. This group can be defined as semi-autonomous vehicles (Moore 1999). These vehicles are a combination of the traditional AGV and an autonomous mobile robot. These vehicle systems have typically a centralised control, and/or man-in-the-loop control. Their objective is to operate in industrial environments, have an easy to use operator interface, and to feature local autonomous navigation on demand.

The SAV concept allows more flexibility to decide on equipment and functionality at a later stage in the design process. An increase in functionality of the vehicles is achieved through the implementation of intelligent distributed control and smart sensing techniques in combination with a modular design approach, see Figure 20 and 21. A semi-autonomous vehicle is an attempt to make i) many decision variables changeable at later stage during the design phase ii) re-configurable by using modules of load-handler, controller, navigation technique, operator interface, etc.. iii) flexibility e. g. to avoid obstacles during operation.

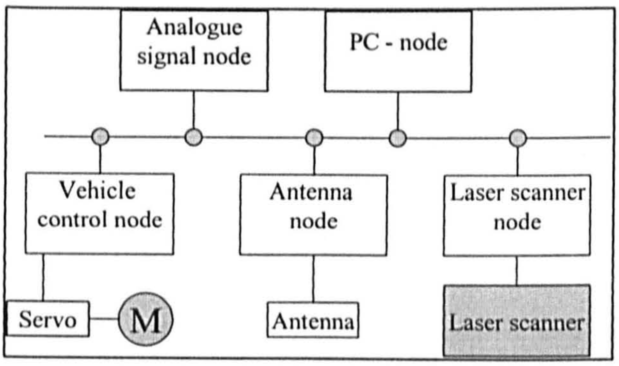

Figure 20, Five of the micro-process nodes in the SAV control system. Specific processors are used for many tasks, e. g. the wire-guidance antenna, laser range scanner, and the PC-communication node. The vehicle control node refers to the drive and steering system, which both are closed servo loops that very accurately position the SAV.

DriveWireToDistance [% of Max. Speed] [Distance]
DriveWireToPlate [% of Max. Speed] [Maximum Distance]
DriveFreeToDistance [% of Max. Speed] [Steering- Wheel Angle]
MoveFixture [Translation length] [Rotation angle]

Table 2, Example of script commands used to control an SAV. The commands are followed by one to three arguments, and control the motion of the vehicle (line 1 to 3) and the load handler (line 4).

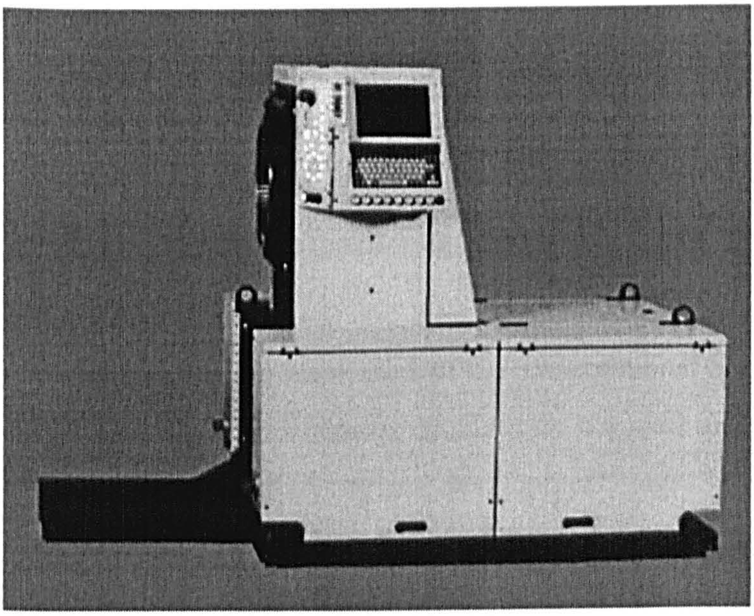

Figure 21, A Semi-autonomous vehicle by Euromation. The load unit at the rear, to the left can handle e. g. gearboxes and car-engines during assembly operations. The operator control interface is an industrial PC with NT operative system, which can e.g. control the vehicle navigation, several states of autonomy, and also provide assembly instructions to the assembly operator.

Figure 21 shows an SAV developed by Euromation and is presented in detail in Moore et. al. (1998). The purpose of the modular approach is to facilitate ease of maintenance, system modification and improvement, combined with faster customisation of the finished product. The concept is illustrated by reference to the vehicle body, which consists of standard modules (or components) which can be arranged in different configurations to create a customised platform (e.g. which can vary in width, length, load capacity, height, drive configuration, etc.). Equally, the control and sensing systems can be configured, re-configured and extended to meet particular application requirements. The initial control system of the Euromation SAV is named Carrier Control System (CCS), and is based on wire-guidance as the main navigation technique. The first three commands shown in Table 2 involves wire-guidance while the fourth command involves an open-control loop navigation, i. e. there are no vehicle position feedback other than dead-reckoning.

Kim and Tanchoco (1990) performed experiments on a similar vehicle which is a tricycle-type free-path AGV equipped with a navigation system based on a dead-reckoning method. It provides the capability to model a variety of system configurations, and allows for complex free-path vehicle manoeuvres such as vehicle take-over, bi-directional flow, multiple vehicle types, and multiple loads on a vehicle. Then the vehicles can operate in complete autonomy without the help of the central controller which serves as a mere monitoring station.

In a heterarchical mode of operation, relatively high-performance processors are required on vehicles since most of the computational burdens are loaded on the vehicle controllers. Since this concept is currently not well understood, more time and efforts are required in the planning and development stages before implementation. However, the system can readily adapt to partial failures of vehicles or communication devices since the operating system does not make assumptions on the number of vehicles in the system or the degree of the reliability of communication (the system performance still depends on these). Thus, the system becomes more robust.

The amount of information to be transmitted is significantly reduced, which makes the communication more reliable. Free-path AGVs add more flexibility to conventional AGV-systems. However, the promised advantages can be achieved only when good control systems are available. While most of existing AGV-systems are operated under a hierarchical control, there exist other modes of operation ranging from the complete heterarchy to the strict hierarchy, and some hybrid methods between these two.

Mellado et. al. (1999) performed similar experiments in the RETRARO project. To adapt to changing production configurations, RETRARO had to provide solutions for the following functionality regarding economical constraints: algorithms for efficient planning and health monitoring; economic sensor systems to provide navigation and obstacle avoidance functions;

According to Shen and Lau (1997) today recent advances in the technology permit vehicles to travel without any physical guide path. Dead reckoning, inertial guiding, and ultrasonic imaging processes are examples of such systems. With virtual flow paths, the system controller can easily alter the guide path layout of the system to reflect the material flow demands.

2.4 Summary of AGV System Design

Due to the flexibility of AGVs they are the focus of much study and development. Novel navigation techniques that are increasingly being used in manufacturing environments place even more emphasis on the design methodology of AGV-systems to make use of their full capability.

The AGV-system design is however a multi-faceted problem with a large number of design factors of which many are correlating and interdependent. Available methods and techniques exhibit problems in supporting the whole design process. A research review of the work reported on AGVS development in combination with simulation revealed that of 39 papers only four were industrially related. Most work was on the conceptual design phase, but little has been reported on the detailed simulation of AGVS. The most investigated design consideration was the AGV-system fleet size.

According to Hoff and Sarker (1998) modification of current research is emphasised to address multi-speed AGVs that may be used more effectively in larger facilities. There is little in the literature about the use of multi-load AGVs. Most methods and approaches presented have their focus in the conceptual phase and there is consequently a lack in the detailed design and evaluation phase.

Semi-autonomous vehicles (SAV) are an innovative concept to overcome the problems of inflexible -systems and to improve materials handling functionality. The SAVs are designed for easy customisation of the vehicle regarding: i) mechanical structure, ii) load handler, iii) navigation functions, iv) sensory system, v) any special behaviour and functionality. Novel approaches to materials handling like the SAV-concept place new requirements on the AGVS development and the use of simulation as a part of the process. There is a considerable potential in shortening the AGV-system design-cycle, and thus the manufacturing system design-cycle, and still achieve more accurate solutions well suited for MHS tasks.

A summary of the design issues has been presented in the modified taxonomy of design and scheduling for AGVs.

3. Simulation of Manufacturing Systems

Simulation has been used for decades to simulate manufacturing systems. This chapter presents the simulation approaches for production engineering. First the strategy and context of Virtual Manufacturing is presented, and then simulation as a scientific method is discussed, followed by simulation in the production system life-cycle.

The following sections present details of discrete-event simulation, simulation methodologies, leading to AGV-systems simulation.

Virtual Manufacturing is aimed at providing a capability to manufacture in the computer. VM is supposed to accommodate the visualisation of interacting production processes, process planning, scheduling, assembly planning, logistics from the line to the enterprise, and related impacting processes such as accounting, purchasing and management. (Lawrence associates, 1994)

One of the main benefits of VM is the potential for shortened production and product life-cycle. In Figure 22 a relating model is presented, the VSOP (Visualisation Simulation Off-line programming and Production) model that has two main processes, the product and production development processes. Products and production systems are developed simultaneously to shorten the time-to-market process according to the Concurrent Engineering concept. Simulation of manufacturing systems should support the production system development at the three levels (Bolmsjö and Gustafsson 1998).

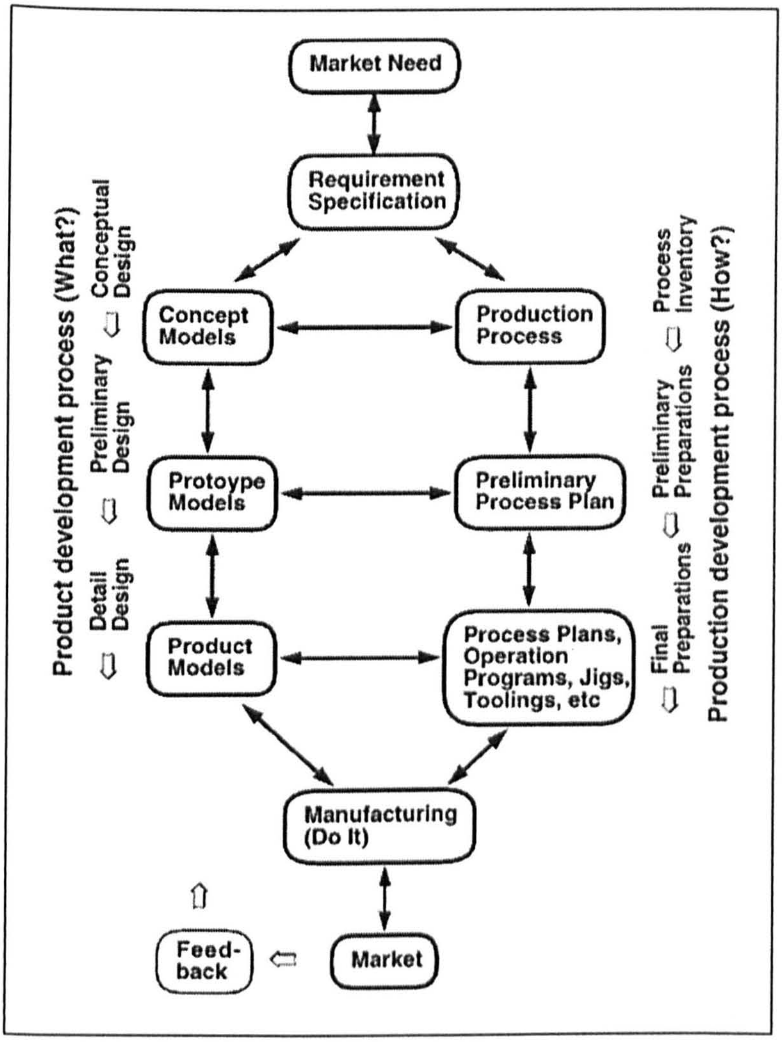

Figure 22, The VSOP model of product and process development.

3.1 Simulation in the Production System Life Cycle

According to Kosturiak and Gregor (1999) a structured and widely applied use of simulation tool can be used for dynamic modelling of enterprise processes. These tools can be used to answers the following questions vital to an enterprise: i) what is to be changed, ii) to be changed into what, and iii) how to change it? The tools can help to identify bottlenecks in the enterprise logistic chain or it can support the decisions concerning investment in new production technology.

Perhaps the best way of modelling complicated event logic is to bear in mind the principle of parsimony, which is to keep things as simple as possible for as long as possible. This requires an evolutionary approach to modelling, starting with a deliberately over-simplified model, which is gradually elaborated until it is agreed to be valid for the intended purpose.

Manufacturing System Design in its Whole Life cycle			**Simulation Model Evolution**
Phase	**Method**	**Function**	
Problem Analysis and Setting of Goals	-ABC analysis -MTM, MOST, etc. -Value Added Curve -Throughput diagrams -Trend Extrapolation -Statistics and Probability Theory	-Products and production Programme Analysis -Process Plan Analysis -Costs analysis -Work Force Analysis -Production Resource Analysis	**Analytical Model for Problem Analysis, Selection of Significant Product Groups, Identification of System Constraints**
Conceptual Design of the Alternatives	-Cluster Analysis -Morphology -Value Analysis -Production Flow Analysis -Analytical Modelling	-Product Family Building -Solution Concepts -Rough Cut Dimensioning -Production System Alternatives Evaluation	**Conceptual Simulation Model for Comparison and Evaluation of the Variants**
Detail Design	-Detail Capacity Design -Material Flow and Information Flow analysis -Layout Planning -Discrete Event Simulation	-Detail Work Place Design -Design of Material Handling and Transportation System, Information Flow, Control etc.	**Detail Simulation Model - Material flow, Information Flow, Control Rules, Cost Flow**
System Installation	-Simulation -Simulation Aided Training	-Simulated Running –in -Personnel Preparation	**Simulator of System Modification Proposals**
System Operation	-Ongoing Improvement Process -On-line Simulation	-Production System Improvement -Testing of the Control Strategies and Decision Support	**On-line Simulation in Production Activity Control**

Table 3, Simulation in Manufacturing System Design. (Kosturiak and Gregor 1999)

Pidd, (1994) presented an introduction to simulation where the following features tend to characterise the systems best suited to computer simulation.

- They are dynamic, that is they display distinctive behaviour which is known to vary through time.

- They are interactive, that is, the system is made up of a number of components which interact with one another and this interaction produces the distinctive behaviour of the system.
- They are complicated, that is, there are many objects which interact in the system of interest, and their individual dynamics need careful consideration and analysis.

Kosturiak and Gregor refer to these tools as Visual Interactive Modelling Systems (VIMS). Examples of VIMS are presented in Appendix 2. These are more general than the specific manufacturing focused DES and GES software tools.

3.2 Discrete Event Simulation (DES)

While differential equations are useful for describing natural systems that vary continuously, many manmade systems are best described as varying in near-instantaneous jumps between discrete states. In both differential and discrete-state models, the values of the state variables change only at simulation clock ticks. So far it is assumed that the simulation clock is periodic and evenly spaced, with an interval of Δt. These simulations are *time driven*. An alternative approach is to perform computations only at significant changes in system state called *events*. In an event-driven model, events are scheduled to occur at particular times in the future. The simulator then looks at the set of pending events and selects the earliest one in that set to be the next event. Once that is chosen, the simulator advances simulation time to that of the next event and then executes it. Traditional programming languages (e.g., C, Fortran, and Basic) can be used to build event-driven models, however software companies have developed specialised discrete-event simulation languages that automatically handle much of the details required to implement a model (Sensors Online 2002).

Discrete event simulation tools for production simulation have been used extensively to develop and optimise AGV based systems. These tools provide the means of realistic shop-floor control, navigation in target layouts with several vehicles, generating performance statistics etc. (Robinson and Bhatia 1995).

Much research on production simulation has focused on optimisation problems, simulation systems often support the detection of bottlenecks etc.. Commercially available systems include Promodel, Witness, and QUEST. A more detailed list is presented in Appendix 2.

These virtual tools can be categorised into 2-D systems, typically with symbolic representation of production entities, and 3-D systems supporting map layouts with recognisable models of machines etc.. The underlying mathematical descriptions can be the same for the two types. AGV-system simulation can be an inherent part of the tool, including kinematics of the machines and moving products, or be a separate unit.

Klingstam (2001) shows how the DES can be used as a tool for continuous process verification in industrial system development. Results include a specification of the working procedures to be used in each life cycle phase of a development project, as well as a definition of the areas where efforts are needed in the future.

Klingstam's (2001) experience from Volvo Car Corporation is that simulation has not been used to its full power. At Volvo, simulation has mainly been used in late project phases to verify an already decided alternative solution or to influence improvements on an existing system. The objective of their research is to outline a way of working with discrete event simulation throughout the life cycle of a development project. There is still much work to be done before this approach is fully accepted by manufacturing and logistical engineers, but there is a need for a technique that provides decision support in the early project phases. Analysing the problem in a structured way can solve much, but there is a need for a tool that can speed up this process. In this sense, it is possible to use DES tools, but they are not well suited for providing rapid answers on a conceptual level. This implies the need for easy-to-use, special purpose tools at this level.

3.3 Methodologies for Manufacturing Simulation

The approaches to simulation methodology are not much different from the engineering development methodology as described in table 3 in section 3.2. Two simulation methods are briefly presented here with similar characteristics. The researchers behind these methods have all much experience of applied simulation (Law and Kelton 2000, Banks 1998).

3.3.1 Structured Simulation Method

Two major methods for simulation in the manufacturing context have been found in the literature: Banks (1998) see Figure 23, and Law and Kelton (2000) see Figure 24. Banks propose a more detailed method while Law and Kelton's method is more generic. Banks' method provide two alternatives on how to proceed if the simulation model is not valid. There are no significant differences between the two methods.

To provide a concise and detailed view of simulation methodologies Law and Keltons method is presented in detail.

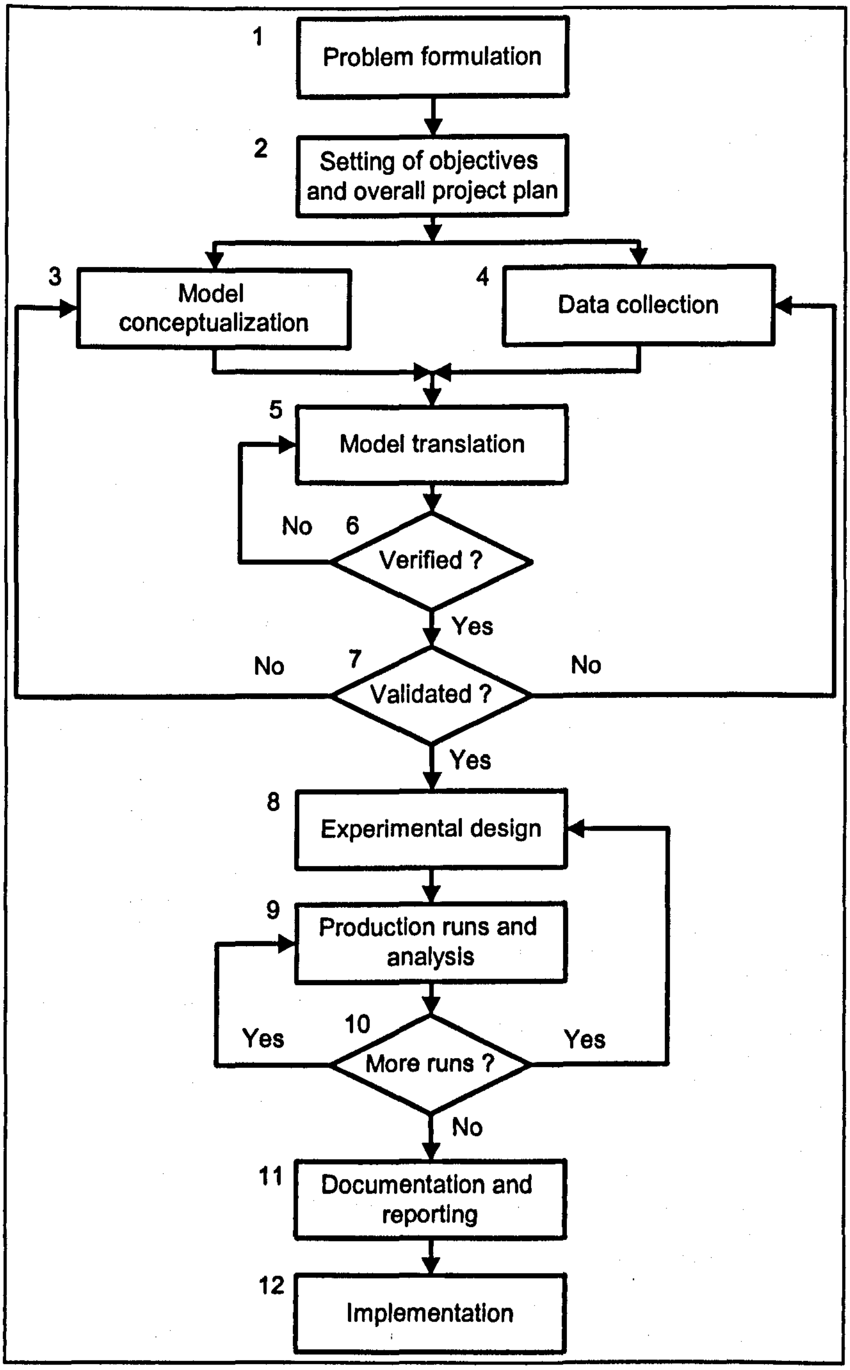

Figure 23, Banks' work model for simulation projects. (Banks 1998)

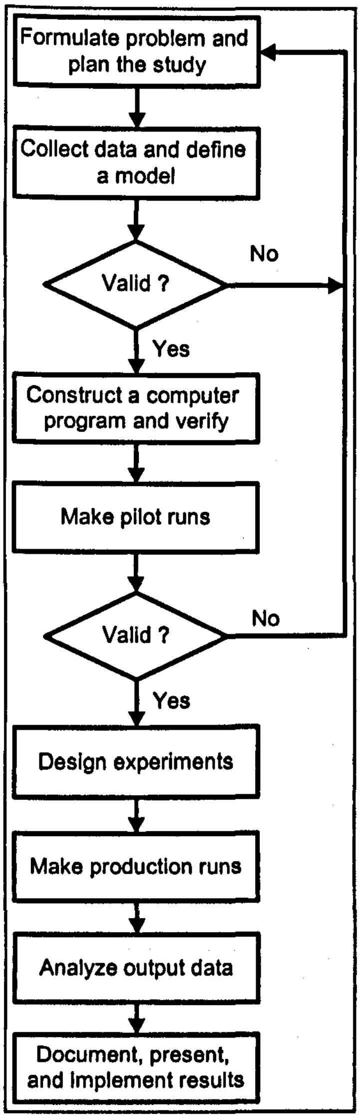

Figure 24, Law and Kelton's work model for simulation projects. (Law and Kelton 2000)

1. *Formulate problem and plan the study.* This first step is crucial to achieve the objective a project within the time and cost frame. It is important to decide the level of detail of the model. Simple enough to be economically justified, but detailed enough to provide the required answer.
2. *Collect data and define a model.* A model is never better than the data used, therefore it is of imperative importance to collect the correct data and use it in a correct way.

3. *Validation.* The validation step warrants the correctness of the model

4. *Construct a computer program and verify.* Choice of simulation software, construction of the computer program as a part of the simulation model and verification that the program and the model behaves as intended.

5. *Make pilot runs.* Test the simulation model to provide data for a second validation stage. Includes debugging of possible program errors.

6. *Validate.* The model is validated

7. *Design experiments.* Experiment design to reach the project objective.

8. *Make production runs.* Carry out experiments.

9. *Analyse output data.* If sufficient data exist, statistical methods can be used to analyse the data.

10. *Document, present, and implement results.* If the results are satisfactory and answer the main question, the results can be used to make a decision for implementation.

3.3.2 Validation and Verification of Simulation Models

One of the most difficult problems facing a simulation is that of trying to determine whether a simulation model is an accurate representation of the actual system being studied, i.e., whether the model is valid. If the model is not valid then the results, from the model would be of scarce value or unreliable. The working procedure used in this work follow the suggested procedure by Law and Kelton given in Figure 25.

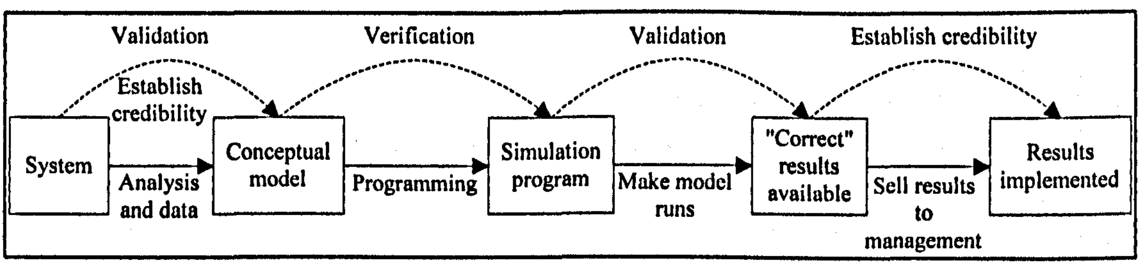

Figure 25, Validation, verification and credibility. Timing and relationships of validation, verification and establishing credibility (Law and Kelton 2000)

Figure 25 shows the timing and relationships of validation, verification, and establishing credibility. The rectangles represent states of the model, the solid horizontal arrows correspond to the actions necessary to move from one state to another, and the curved dashed arrows show were the three major concepts; validation, verification and establish credibility, are most prominently employed.

3.3.2.1 Level of detail

When the level of detail of the simulation model is considered it is important to be aware of that a good simulation model does not need to have a one-to-one representation with the real system. There are several aspects that affect that level, time, money, computer constrains and simulation purpose with the model. If a simulation model is created to measure e.g. throughput then the detail level chosen is the one adequate for that purpose, which is different to the detail level for a model able to measure required floor space. An important suggestion is not to have more detail in a model than is necessary to address the issues of interest, subject to the proviso that the model must have enough detail to be credible. This final statement suggests that it might be necessary to introduce some details just for the credibility aspect.

The type of data available influences also the detail level. If the simulated system does not exist then it would be obviously much more difficult to create credible data, but if the simulation model has the purpose of fine-tune an existing model, then the data is probably accessible and the model can be done much more detailed (Law and Kelton 2000).

3.3.2.2 Verification of a simulation model

Verification is determining that a simulation program performs as intended, i.e. debugging the computer program. One of the techniques during verification is called "trace", by tracing the state of variables, the behaviour of a program can be monitored.

Also, graphical simulation gives the opportunity to verify the logic by simple visual check of the system behaviour.

3.3.2.3 *Validation of the model*

A model is always a simplification of the real system, which means that validation of a model is not a verification of the exactness of the model vs. reality. Validation is concerned with determining whether the conceptual simulation model is an accurate representation of the system under study. The validation procedure is done during the whole project and not just by the end of it.

3.3.2.4 *Developing a model with High Face Validity*

The primary objective during this first step is to develop model with high face validity, i.e. a model that on the surface seems reasonable to people who are knowledgeable about the real system.

The purpose of the second and third step is to quantitatively test the assumptions made during the initial stages of model development and establish how closely the output data resemble the real system output.

The use of manufacturing simulation has largely been adopted by the car manufacturing industry that has recognised the benefits of the Virtual Manufacturing Concept. According to Williams and Orlando (1998) discrete-process simulation analysis supports assessment of the need for and quantity of equipment and personnel, and assessment of operational procedures. This is achieved via a construction and examination of a model relative to system performance evaluation. A vital part of any simulation study is setting clear project goals initially (Banks and Gibson 1996), especially since project scope, model design, and data collection efforts must be defined in the context of those goals.

3.4 Simulation of AGV Systems

Simulation, which is one of the main tools for AGV System design is presented here. Many aspects of AGV-simulation have already been presented in sections 2.1 and 2.2 since a clear distinction between AGV-simulation and AGV-design is difficult to make.

Ülgen and Kedia (1990) criticise many simulation approaches to AGV-system design. In their literature review the authors found the following assumption regarding AGV simulation:

- Blocking time is assumed to be zero.
- Vehicles do not pass each other.
- Travel times do not incorporate acceleration and deceleration.
- Empty vehicle travel is not accounted.
- Number of AGVs is fixed.
- Vehicles are always dispatched to pick up or drop off complete loads (i.e., load splitting is not permitted).
- Travel times between load/unload points are based on shortest route distances.
- Track layout is fixed.
- Guide path direction is fixed
- Load-unload points are fixed.

The following is a list of the objectives considered by past researchers:

- Determine minimum number of AGVs required.
- Minimise the total travel of loaded vehicles.
- Minimise the total travel of vehicles (loaded + unloaded).

When designing and planning an automated material handling system, a large number of factors must be considered. In particular, with an automated guided vehicle (AGV) system, things such as the number of vehicles, a guidepath network configuration, control logic for dispatching vehicles, routing of vehicles from origin to destination, and interface with other material handling systems must be considered. Although much work has been done in the design and analysis of AGV-systems due to the complexity of these systems, simulation has been used as the primary analysis tool in designing, planning and analysing AGV-systems. Much of the modelling and simulation in the literature of material handling systems have been done by general-purpose simulation languages such as SIMAN or SLAM, see Appendix 2 for a complete list. Recently, material handling features have been added to SIMAN and SLAM, however these features are not flexible enough to serve as a basis for simulating the great diversity of many alternative material handling systems. Some manufacturing simulation systems such as FACTOR, XCELL+, MAST, PROMOD, and SIMFACTORY have modelling constructs for manufacturing systems including an AGV-system. However, these systems are also inflexible in that they are limited to modelling only those manufacturing configurations allowed by their standard features. Some of these limitations are:

- Vehicle breakdown is not considered.
- Battery recharging of vehicles is not considered.
- Vehicles travel with instantaneous acceleration and deceleration.
- Vehicles do not pass each other.
- Vehicles travel based on the shortest path.
- Vehicles transport one unit load at a time.
- First-in-first-out (FIFO) is used for the vehicle initiated rule (closest free).
- Shortest travel distance rule is used for the workcenter initiated rule.
- Only one vehicle can occupy a zone at one time.
- Idle vehicles are sent to the staging area (parking zone, one of several).
- The routing sequence of each part type is deterministic.

According to R. McHaney (1995) a major supplier of AGV-systems indicates over 80% of the customers interested in purchasing an AGV System had either completed a simulation or required a simulation be completed prior to system installation. Widespread use and understanding of computer simulation techniques by both customers and competitors of industrial automation equipment vendors have forced modellers to continually improve the accuracy of simulations.

3.4.1 Semi-autonomous Vehicle simulation

Simulating SAVs is different from traditional AGVS simulation. The old paradigm of how an AGV-system behaves are no longer true for modern AGV-systems, e. g. assumptions of no obstacles present, strict control hierarchies with little vehicle autonomy, and centralised control with little on-board processing capacity. If the AGV technology of today is to be used to its full power, design and evaluation tools are needed, e. g. simulation (Moore et. al. 1998).

The main concept behind Semi-autonomous vehicles is to increase the autonomy of AGV's but with the operator still in the control loop. Much research in mobile robotics takes a fundamentally different standpoint in which a high degree of autonomy is desired (Everett 1995). The tasks to be solved are e. g. navigation without a priori knowledge of the environment, finding a goal in such an environment, autonomous obstacle avoidance etc.. The SAV concept can be considered as a bottom-up approach starting from the industrial requirements, while the previously mentioned mobile robotics research takes a top-down approach, developing autonomy and then finding potential applications. Many influences from this field have resulted in novel navigation techniques e. g. sensor fusion, Artificial Neural Networks (ANN), and Fuzzy Logic (FL), but also sensor applications novel to AGVS e. g. laser range scanner, advanced ultrasonic sensor systems (Kazys 1998), etc.. An SAV application has been developed by Euromation (Moore et. al. 1998) to increase AGV functionality. The vehicle is described in section 2.3.4. One of the main concepts is a modular vehicle design which accommodate the customisation of navigation systems and sensors, load handlers, operator interface, type of control hierarchy, etc.. Several navigation systems and techniques can be used depending on the material handling and location specific requirements. E. g. dead-reckoning will in most cases be used as one source of information since it is readily available and accurate within a few cm assuming no slippage and for shorter distances (less than 10 meters). The main navigation method for the Euromation SAV applications is still wire-guidance, which is despite its low flexibility popular since it is very reliable. There are several other navigation techniques and sensors that can be used e. g. the SICK laser range scanner, and the NDC laserway navigation system (presented in more detail in section 2.3.3).

Eriksson and Moore (1995) used a simulation environment to train a reactive robot to learn to respond to sensor information. Four ultra-sonic sensors were used for navigation and the reactive control structure based on Artificial Neural Networks (ANN) of the robot was trained for obstacle-avoidance, wall-following, and corridor-following. The algorithms that were developed in the virtual environment were transferred to a real mobile robot. Tests showed that the real robot had attained the behaviours and could make use of them in the real environment. The virtual environment included sensor simulation to accommodate for the training of ANNs.

3.4.2 Sensor Simulation

There is an obvious need of sensors for mobile robotics and for AGVs. The need of simulation software that includes sensor-simulation is apparent for more realistic simulation of sensor-based robots. Eriksson and Moore (1995) propose a generic sensor model tested on proximity sensors, optical sensors, and ultrasonic sensors, see Figure 26. The models were implemented in a Computer Aided Robotics system. The implemented sensors are independent devices that have their own task programs, which control the sensors behaviour. These programs run concurrently with all other programs in the simulation environment. The robot programs and objects in the environment interact as necessary with the sensors.

A three-dimensional line-segment can be used to approximate the characteristics of a proximity sensor. During the simulation the line is checked for collisions with all objects in the environment. If any collisions are detected, the distance to the object closest to the sensor body is used. For other sensors as non-contact ultra-sonic sensors, a cone can be used as the shape of the active region. Eriksson and Moore (1995) states that it is necessary for the simulated sensors to have operational characteristics that are similar to the real device, namely the detection range and the output format. This way objects that come into the detection range should be detected at the right moment. The output channel of the sensor can be a limiting factor depending on the update frequency of the sensor, and the output format influence the resolution of the sensor data. Figure 26 shows the generic sensor simulation concept.

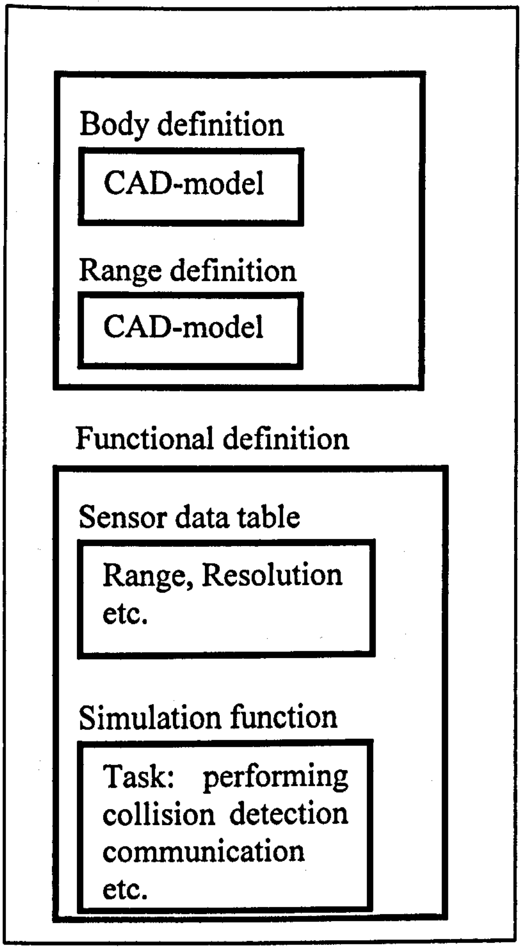

Figure 26, Generic sensor model proposed by Eriksson and Moore (1995). The model is divided into the sensors geometrical representation and its functional definition. It is necessary for the simulated sensors to have similar operational characteristics to the real devices.

A detailed model of an ultra-sonic sensor can be modelled in the following way. The detection volume is represented as a cone and at the cone perimeter there are four trace-lines (or detection lines) with the same angular distance in-between. Figure 27 shows the steps of the control program for a sensor.

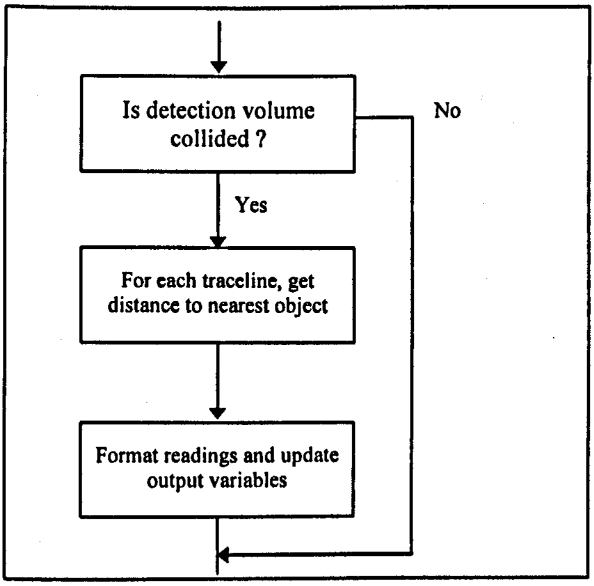

Figure 27, Steps in the control program of the sensor model.

The task-program for the sensor will operate as:

1. Check for collisions between detection cone and other objects
2. if collision then check for collisions with trace-lines
3. if collision with trace-line then use shortest distance for sensor output
4. else no object detected as sensor output
5. format sensor output and send to output channel
6. end of collision check

This collision check will be performed with the same update rate as the real sensor to model the dynamic behaviour. For line 2, because of different reflection characteristics for various materials, the angle between a detected object and the trace-line is calculated. If the angle is within a specified range, the object is detected, otherwise no reflection from the object is assumed and it remains undetected.

By first checking the detection volume of the sensor, the processing complexity is kept low, which is also the reason for using as few trace-lines as possible.

3.5 Summary of Manufacturing Systems Simulation

Virtual Manufacturing is aimed at providing a capability to manufacture in the computer. VM is supposed to accommodate the visualisation of interacting production processes, process planning, scheduling, assembly planning, logistics from the line to the enterprise, and related impacting processes such as accounting, purchasing and management.

Simulation is used to support most aspects of the production systems engineering life-cycle. Existing simulation methodologies support well these aspects. There is however a lack of detailed simulation methodologies for the AGV-system development. Novel functions of AGVs are not supported by traditional AGVS design approaches, and generic simulation methodologies are not tailored to accommodate the complex considerations of AGVS design.

A large number of factors must be considered in the design of an AGVS, such as the number of vehicles, a guidepath network configuration, control logic for dispatching vehicles, routing of vehicles from origin to destination, and interface with other MHS. Much work has been done in the design and analysis of AGV-systems but due to their inherent complexity, simulation has been used as the primary analysis tool in designing, planning and analysing AGV-systems. Some of the modelling and simulation of MHS have been done by general-purpose simulation languages. However these are not flexible enough for simulating the great diversity of many alternative MHS. Some manufacturing simulation systems also have modelling constructs including AGV-systems. These systems are also inflexible in that they are limited to modelling only those manufacturing configurations allowed by their standard features.

3D graphical discrete event simulation tools for AGVS design and development have existed for a decade, but not much work has been reported on the use of 3D graphical Geometry simulation systems to simulate AGVs. Still, research in the area of 3D sensor simulation has made it possible to simulate the operation of individual AGVs.

Much research reported in literature focus on deciding the AGV-fleet size. The simulation based method used by a Bilge and Tanchoco is in many aspects superior to most other methods. It is applied in the detailed simulation phase of AGV-system design. When detailed aspects of importance have been included in the simulation model several fleet-sizes are tested for key performance measures. It can be useful to test several scenarios, also including worst-case scenarios. These are important if some of the data is estimated or in other ways inaccurate. The fleet-size will be the result of detailed considerations of the AGV-system and its environment, e. g. production data, failures and other disturbances, battery-considerations, idle-vehicle location, and dynamic phenomenons in the material flow. No other reported method reach the same accuracy. The main disadvantages of this method are:

i) It is time consuming.

ii) Potentially costly in terms of software and time.

iii) Too cumbersome for small AGV-systems where a simulation study is not necessary for deciding other aspects.

If simulation is used for strategic or other reasons, the detailed simulation approach shows considerable advantages to produce accurate AGV-system designs.

In other engineering areas e. g. Computer Aided Robotics, simulation is used for detailed design, development, and evaluation to the extent of including off-line programming, i. e. downloading virtually developed control code. This highlights a gap in the AGV-system design methodology concerning the use of simulation.

4. Research Strategy

The research carried out during this PhD-project is presented here. A discussion and motivation to the choice of method is provided along with a description of the studies.

The principal aim of this research is the advancement of simulation in the design of Automated Guided Vehicles.

The detailed objectives of the research were:

i) A literature survey in the areas of AGV-system design and simulation.

ii) To study SAV-simulation and develop a virtual environment for SAVs which supports the development of novel functionality.

iii) Identify factors and complications of industrial AGVS analysis and simulation, including large size AGV-systems.

iv) Develop a unifying framework for the design process of AGV-systems.

The result of the first objective has been presented in chapter 2 and 3. Three research cases were designed to meet the second, third and fourth objective. These cases are briefly discussed in this chapter. They presented in detail in chapter 5 to 7.

4.1 Choice of Research Studies and Experimental Design

In the Agile Manufacturing paradigm adaptability and fast response are keywords. This implies that the case studies of this research take into consideration fast adaptability and reconfiguration of material handling systems regarding production volume, product variants and changing production flows.

The case studies should cover the different aspects of:

- Developing functionality of AGV's and SAV's.
- AGV-system management, which includes intricate problems of guide path design, dispatching of loads to be moved, vehicle routing and traffic control.

- Relevance to industry.
- Simulation based but related to real AGV-systems. Real environments in this context are laboratory or industrially based.

One main feature of SAV's is the possibility to add functionality. The examples were needed to be novel compared to traditional wire guided vehicle systems. The comparison is made between a traditional AGV-system and one equipped with extended functionality and this way an evaluation is made between the two.

The first research case is designed to approach the third objective of this thesis: Identify factors and complications of industrial AGVS analysis and simulation, including large size AGV-systems. In the literature little work has been reported in the area of industrial AGVS simulation, four of 39 papers related directly to an industrial case. The motivation and main objectives for this research case was to identify relevant factors important to industrial AGVS simulation. The research case is described in detail in chapter five, Identification of factors for industrial AGVS simulation.

The second research case is designed to approach the second and fourth objective of the thesis: to study SAV-simulation and develop a virtual environment for SAVs which supports the development of novel functionality, and develop a unifying framework for the design process of AGV-systems. The work model will strongly benefit from an industrial simulation study that includes the development of a virtual environment for the design of novel functionality of AGVs. The research case is described in detail in chapter six, Simulation in the design of semi-autonomous vehicles.

The third research case also approaches the fourth objective by evaluating the unifying framework proposed in the second research case. The objective of this research case is to evaluate the methodology with focus on industrial relevance, a complex environment to simulate, and the addition of functionality to the simulation model. The simulation model was used to analyse important design aspects by which the methodology was evaluated. The research case is described in detail in chapter seven, Evaluation of AGV-design methodology.

5. Identification of Factors for Industrial AGVS Simulation

In this chapter the results of an industrial research study is presented. The project was conducted at the J-division, Eastern Engine Plant, Volvo Cars, Skövde, Sweden during the spring of 2001. The project resulted in a validated model of the crankshaft-production-line with an AGV-system of 29 vehicles in full operation. This model has been very useful to perform detailed, credible, and realistic AGVS-simulations.

5.1 Introduction

In the literature little work has been reported in the area of industrial AGVS simulation, four of 39 papers related directly to an industrial case. The motivation and main objectives for this research case was to identify relevant factors important to industrial AGVS simulation. The secondary objectives where: i) to study operational factors in AGVS-operation, ii) to carry out a realistic validation process on a considerably large and complex AGV-system. This approach is intended to focus on the industrial problem and thus not make assumptions that are less realistic which happens in some conceptual design studies.

The simulations using the validated model gave the following results:

- Increase of vehicle speed on certain high-speed sections of the guidepath layout showed a small improvement up to a certain level of throughput.
- The AGV-system does not affect the productivity of the production line in a negative manner. The results show that the bottlenecks are in the workcells and not in the AGV-system.
- The system is sensitive to batch size reduction due to increased amount of set-ups and as a result decreased throughput of the line.

Valuable insight were gained in the simulation process of industrial AGV-systems such as analysis, model building verification and validation, experimenting and documentation of results according to the operation and improvement of a large-size AGV-system.

The test scenarios have been designed to in the best way accommodate the objectives of the study. This work is the base to a simulation methodology for AGV-system design.

5.1.1 Objectives of Study

The main objective of the study was to produce an industrially relevant simulation model of a large-scale AGV-system. The influence of several major design parameters on the throughput and work-in-process of the system were studied. A secondary goal was to improve the output of crankshaft production and to study system losses, by evaluating alternative production control scenarios. The following parameters and their effects were studied:

- The influence of varying vehicle speed for path sections.
- If the AGV-system has a negative effect on the throughput of the system, i. e. if the AGV-system is the bottle-neck.
- Change of cell logic, i.e. early release of crankshaft pallet from machine.

The simulation study was performed using the simulation tool Quest by Deneb, USA (Deneb 1999)

5.1.2 Acknowledgements

The author wishes to thank the production staff at J-division, Volvo for all their help regarding this project, especially Gunnar Hellichius.

The project was to a large extent undertaken by a group of MSc students as part of their MSc studies. A special thank is extended to Matias Urenda Mores and thanks to Christian Leijon, Peter Wells, and Thomas Karlsson for their help in the project.

The author also wishes to thank Gunnar Nordsten, University of Skövde for valuable support.

5.2 Test Scenarios

The test scenarios have been designed to in the best way accommodate the objectives of the study. Much effort has been made to develop a valid simulation model and to assure its correctness. The first scenario is consequently to mimic the operation of the manufacturing system to verify that the behaviours match. After the model was validated five additional scenarios were set up to manipulate the model and find potential benefits of changed design variables of the AGV-system. This work will provide additional input to a simulation methodology for AGV-system design.

The main concept of the following four scenarios is how the travel velocity of AGVs influence the throughput of the manufacturing system.

Test Scenario	Description	Result
1	Validate simulation model	High model validity achieved, 3% difference
2	Study AGVs with no speed change	
3	Study AGVs with speed 1.1 to 1.3 m/s	
4	Test change in workcell shipping logic	Decrease in Work In Process

Table 4, Test scenarios for simulation in industrial AGVS design. The four test scenarios of the simulation project at the Volvo Engine Plant, Crankshaft Division.

5.3 J-division of the Volvo Car Company Engine Plant in Skövde

The case study involved the Volvo Car Company's J-division in Skövde, which is a car engine crankshaft plant. The degree of automation is very high and the complete Volvo Eastern Engine plant is recognised as a leader in effective production of car engines. Figure 28 shows an overview of the plant.

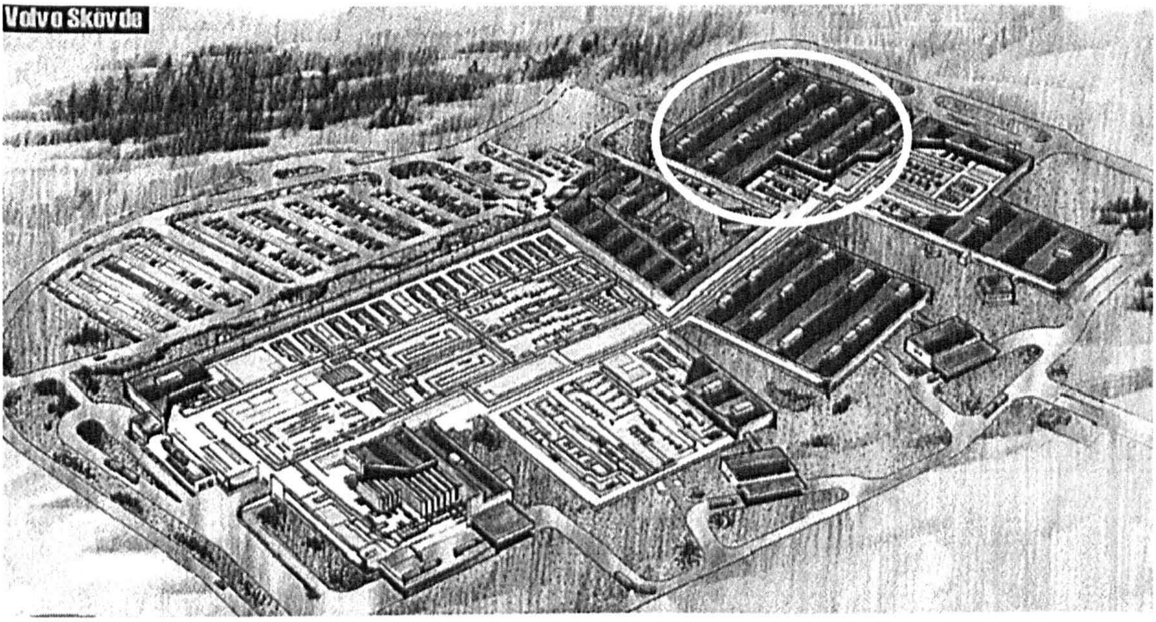

Figure 28, Overview of the Volvo Engine plant. J-division crankshaft line is the uppermost right section of the plant indicated with an oval. The AGV-system studied is one out of eight AGV-systems in the plant.

The plant produces four, five, and six-cylinder engines of a large variety of models with options as turbo etc.. Accordingly there are eight types of crankshafts that are produced at the J-division. The production is divided into 32 workcells which perform operations on the raw-material forming it to finished crankshafts. The layouts of the workcells are three large ovals where firstly rough-cut machining, secondly fine-machining, and finally grinding is performed. At the end of the line is an intermediate high-store buffer where the products are stored before entering the internal assembly engine line.

The materials handling is carried out by an AGV-system which transport the crankshafts on special pallets 20 by 20. One AGV can carry one pallet either loaded or unloaded. Between all the workcells the pallets are moved by AGVs which result in a considerable number of transportation tasks. This is carried out by 29 AGVs. The AGV-system is a moderately old system using inductive wire-guidance for navigation. The guide-path layout is uni-directional with zone-blocking for traffic control. The dispatching rule chooses the closest free vehicle first for a delivery task. There is no planning ahead capability implemented to improve performance.

5.3.1 The production control of the J-division plant

The basic principle of control is pull-demand just-in-time. This is combined with manual control of the work-in-process level of the system and the part mix.

The production flow is line-based and the crankshafts travel from one cell to another on pallets. Some cells have multiple functions or machines to balance the total cycle-time of the cell. Each workcell place material requests to fill its local buffers. These have a capacity of one pallet, see Figure 29.

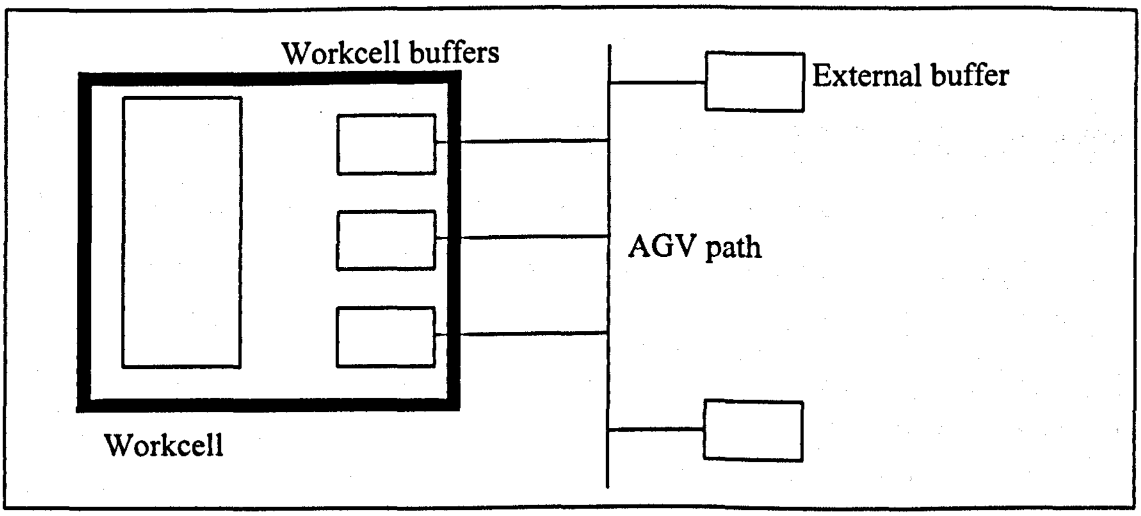

Figure 29, Workcell layout. The workcell includes one machine, three workcell buffers, and two external buffers. Parts in the workcell are handled by an overhead-gantry which defines the boundary of the cell.

Most workcells have three buffers from which parts are picked, machined, and put back in position. Once the operations are made to the parts on a pallet it is requested to be removed from the workcell. If there is space in a downstream workcell, which can perform the next operation, a transport request is issued and the move is made. As second priority a check is made for space in the external buffers of each cell. If no space is available there the workcell becomes blocked.

At the beginning of the production line parts enter the system. This workcell is manually operated and the total work-in-process is controlled not to become too high and cause congestion in the system. A logistics manager decides the actual part mix of crankshafts to be produced to keep the safety stock up-to-date.

5.4 Simulation model of the production system

The simulation model was developed in Quest DES-simulation software. Quest provides both an interactive simulation interface, and an application language for the programming of non-default objects. Many of the default objects have been used, e. g. machines, buffers, but application programs were also developed for the AGV-system functionality. The simulation of AGV-systems in Quest is presented in section 7.3.

The purpose of the model is to accurately simulate the flow of material through the J-division plant. The main entities of the model are workcells, AGV-controllers, AGV's, buffers and parts. Parts are represented as single pallets carrying 20 crankshafts. The individual workcells are modelled as single functional units regardless of the number of machines in the real system. This limits the model complexity to a manageable level, thus the overhead gantry, all machining centres and other surrounding equipment are considered as one machine. All input data, e.g. workcell cycle time, machine set-up time, number of batches and size, is gathered by the simulation software from an excel worksheet at the start of each simulation run.

5.4.1.1 Design of Workcells

The work-cells in the J-division have one or more machines in each work-cell, so each work-cell was created separately with the right number of machines. A CAD-layout of the J-division was the base for the modelling and it was used to regulate the size of the over-head gantries so it would fit when the complete model would be assembled. Figure 30 shows a standardised model of a workcell. The geometrical representation is similar for all workcells, but they occupy the same space as the real workcells.

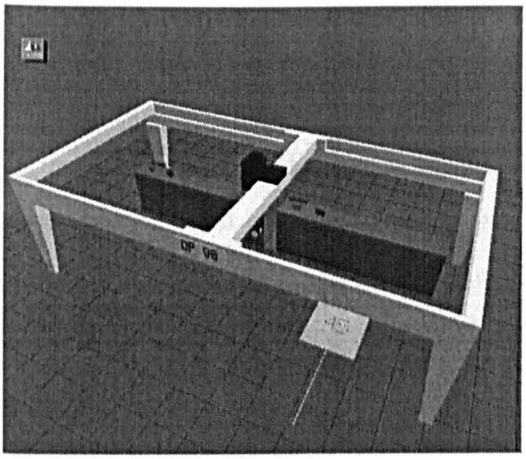

Figure 30, Standardised model of a workcell.

5.4.1.2 AGV System

The AGV-paths are represented by segments either a straight lines or curved sections. AGV segments form the AGV path systems on which AGVs can travel.

A CAD-layout of the plant was used to import the AGV-path into QUEST. Serving as a background all of the AGV-segments where created. Load and unload points for the AGVs are decision point, which act as local controllers, which are also used for zone-control and traffic management. More than 200 decision points were created for the simulation model. The AGV controller is used to globally control one or many AGV classes with respect to a set of AGV decision points. A controller can provide instructions to AGVs concerning which path to take and can select which AGV to use for a given task. It represents a predefined material-handling construct that can transport multiple parts from one AGV decision point to another.

5.4.1.3 Production Buffers

In the crankshaft production line there are four buffer positions in each workcell, three for normal use and one for defect crankshafts (Not In Order, NIO). The flow of defect crankshafts were not included in the simulation. This does not affect the results since defect crankshafts are handled manually.

In the simulation model workcell buffers are modelled in pairs of input-output with the same geometrical position. Such a pair represents one physical buffer. When an AGV delivers a pallet to a workcell it is placed at an input buffer before being logically transferred to one of the machines. After machining all 20 parts the pallet is moved to an output buffer. The production line also makes use of external buffers for queuing to downstream workcells. These were modelled as default buffers with capacity of one pallet.

5.4.2 Material Flow Through the Simulation Model

To define the material flow in the logical system connections have to be made and also logical selections included where appropriate. The flow starts at a source element where pallets enter according to the production plan which is a file in excel-format (an example is shown in Appendix 3). Connections are then required to and from each element that handles the pallets e. g. AGV-decision-points, buffers, and machines though not each individual AGV. Finally the flow is terminated at a sink where throughput data are collected.

To mimic the properties of the real production line a combination of push- and pull-methods are used. The production control of the real system is a mix of pull and push methods. The production manager's objective is to uphold certain levels of crankshaft variants in stock. This is achieved by using demand-forecasts, stock levels, and work-in-process in the system to produce production orders with variants and batch-sizes. Work-in-process in the production system is kept below 2000 crankshafts to decrease risk of congestion.

There are two types of connections in Quest, pull and push connections

- Pull connections

  The pull mechanism allows parts to be created on demand. Demand typically arises at the sink and is sent in the form of a request for a particular part to the upstream element, which tries to satisfy it. If the element has the requested part, it is transferred. If it does not have the requested part, it propagates the request upstream. Requests travel in an direction opposite to the material flow in the system.

- Push connections

  The push connections are the connections between elements that transfer parts downstream.

5.4.3 Structure of Simulation Model Logic

The logic of the real manufacturing systems is very complex and impossible to imitate using basic functions in Quest. Special application programs were developed to control the behaviour of the elements in the model. The application programming language in Quest is SIL which is a Pascal-based high-level language with additional discrete-event simulation functionality. By developing the application programs it was possible to achieve a behaviour that closely resembled the real system.

Each element in Quest uses at least 4-5 processes in its execution. These processes have different tasks and are interacting during a simulation run.

- **Request logic:** receives and sends requests. A request is an order for a specific part which is sent upstream. The request process makes calls to request propagation logic and to the route logic.

- **Request Propagation logic:** is used to determine how the request is to be propagated upstream.
- **Process logic:** is activated when a part arrives to an element and a work process can be executed, i. e. when other resources that are required are available. The process logic calls the route logic when it is finished and the part is to be routed out from the element.
- **Route logic:** routes the part from the element.
- **Init logic:** is executed at the beginning of a simulation run to initiate variables.

5.4.4 Assumptions in the Model

The challenge of a simulation study is to reach a sufficient level of detail of the model which still can produce the requested results. All models are obviously simplifications of the studied system. It is nevertheless important to clearly state these limitations of the model so that the results can be critically examined in the light of the made assumptions. This is a vital step in the simulation methodology suggested by Law and Kelton (2000).

The following assumptions were made concerning the model in this research study:

- Workcells are modelled as machine elements. This level of detail is chosen since workcell data existed but no specific data on gantry handling time, machining time etc.. A more detailed model will also increase complexity considerably without a presumed improvement of the results.
- Workcell failure data are non-dynamic. No distributions were used to represent the failures as the raw data was not sufficient for such an approach. The failure data used from the production follow-up from week 41 of 2001 was not very representative as some major overhauls were made that week. This does however not affect the validation scenario since the production results of week 41 still can be compared with the results of the model. For the velocity test scenarios no workcell failures are used to allow an unbiased comparison, assuming that the failures would have a very similar effect on all four scenarios.

- Flow of defect products is not considered. This is handled manually by operators and is a low percentage of the total flow.
- Default Quest AGV control logic is used. The real system control logic cannot be modelled in detail since the algorithm is unknown (business secret of the AGV supplier). On-site observations did not contradict operational similarity. Any significant differences between the real AGV-system control and the Quest default AGV logic is assumed to be found during the model validation.
- AGV recharging time is not considered. It is assumed that the AGVs have enough idle time to recharge, or that the system is not operated around the clock. If that is the case the results are likely to be overly optimistic for the tests made with fewer AGVs than 30.
- AGV failures are not considered. Occasionally the real AGVs failed e. g. losing their guidepath and causing congestions. This was estimated to have little effect on system performance provided that operators were fast to detect and address the problem.
- AGV parking procedures are not consistently modelled. The real system AGV parking rule is a combination of 'Stop when idle' and 'Park at designated position'. The model used only the latter with specific parking places at buffers located outside workcells. Occasionally congestions were caused by the 'Stop when idle'-rule though the real controller solved these problems with a resulting time delay. This assumption is likely to generate somewhat optimistic results for test scenarios with more than 30 AGVs since these are more often in an idle state.

5.4.5 Input Data

The quality of the input data is vital for a simulation study. Law and Kelton (2000) use a method for ensuring input data quality.

All production data used in the model originates from a thorough production capacity analysis, which was conducted at J-division by Volvo personnel during week 41 in 2001 (Appendix 3). The data used in the model for the workcells are cycle-time, set-up time for machines, Mean Down Time (MDT), Mean Time Between Down (MTBD), batch data, and AGV-data. These are defined as:

Cycle-time in seconds, time for performing operation on crankshaft

Set-up time. The total time (in seconds) for all set-ups divided by the total number of set-ups in the data. For workcells with more then one machine the set-up time is the sum of all the machines.

MDT (Mean Down Time) is the average time a workcell is unavailable for production due to repairs and service. The MDT does not include set-up time. If a cell contains more then one machine the used MDT is the average sum of all machines in the cell.

MTBD (Mean Time Between Down) is the average time a workcell is functional.

All cell data is stored in an excel worksheet (Appendix 3) which is entered into the simulation software by each workcell in the initiation sequence of the simulation.

Batch data used to verify the model originates from the real data used for the batches manufactured during week 41, in 2000. Batch sizes are not smaller than 500 due to the production loss during setup times. During week 41 17 batches were produced of the eight possible product variants.

AGV Data used in the model was gathered during on-site observation. The average velocity is 1 m/s (metre per second) on straight path-segments and 0.6 m/s on curved segments. Acceleration and deceleration was observed to be 1 m/s*s. The load and unload procedure takes 45 seconds for all load and unload stations.

5.5 First Test Scenario: Validation of simulation model

The objective of the first scenario was to validate the simulation model. The real system data was compared with the simulation model data, showing a good similarity. The average number of produced crankshafts per hour in the real system was 73 per hour. In the simulation the average became 75.4 per hour, a difference of 3,8 %.

According to Law and Kelton's (2000) simulation methodology the validation phase was conducted before making experiments. Real system data from week 41 in year 2000 was used for the validation phase. The production orders from that week were used to control the simulation model, and the results were compared with those of the real system. If a close resemblance can be shown, the model is considered valid within the given limitations of the validation data. The data for week 41 originates from a capacity follow-up performed by the production team at Volvo Cars. The batches that were manufactured during that week are also presented in appendix 3, it corresponds only to four days production. The reason for this is that the division had a major stop during one day, which is not representative for the overall production.

The results from this simulation show a good similarity with the results from week 41, the average number of produced crankshafts per hour in the real system was 73/h. In the simulation the average became 75.4/h, the difference only being 3,8 %. This is naturally only one week of production, which is not representative for all other weeks. Also, the hourly output varies over the days and weeks. It is still believed after discussions with experts, i. e. production managers, operators, and logistics managers, that the model represents the real system well. Historical data for e. g. one year was not used since many changes had been made to the system which caused variations over the year. Also one of the intentions was to study the system of today, and to analyse future changes.

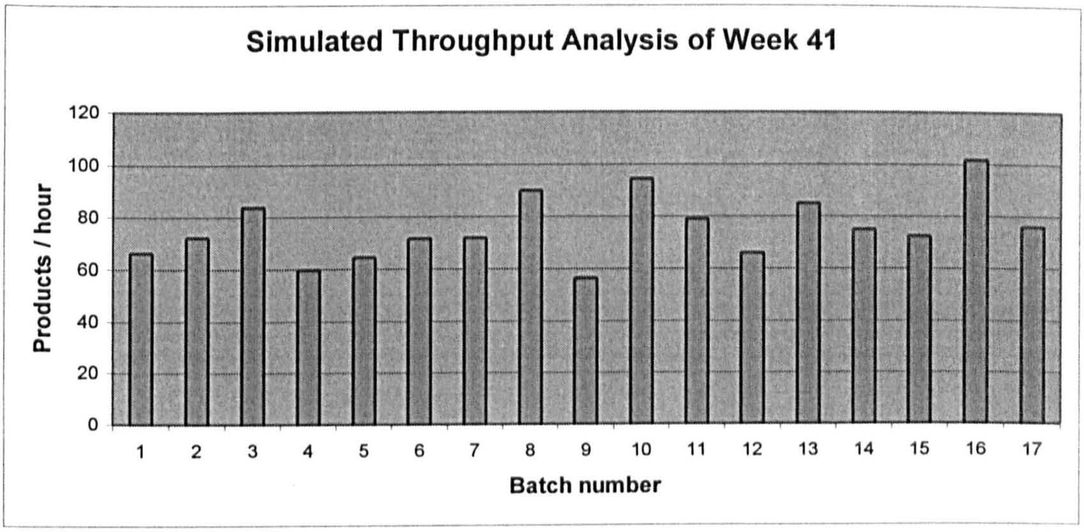

Figure 31, Production rate per hour during the simulation of week 41. The data were collected once during each of the 17 batches produced during that week. The average production rate was 75.4 products per hour.

Figure 31 shows how the average production of crankshafts varies during the four days of production during that week. The readings were done once during each batch.. The average value during the simulation was 75.4 products per hour. The total time to produce the 17 batches was 93.22 hours approximately 3.9 days.

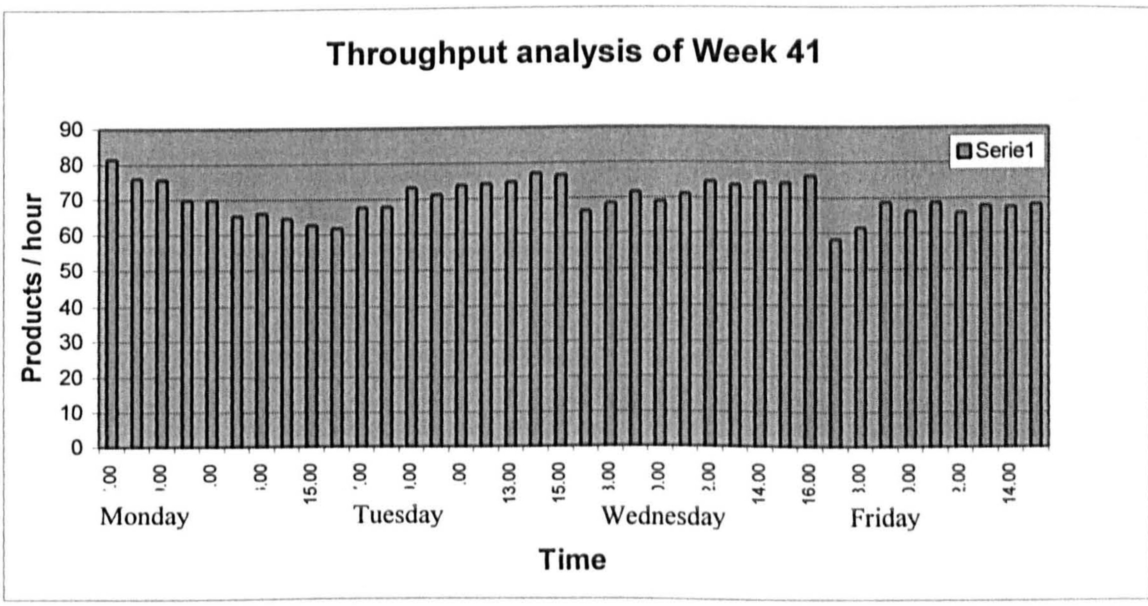

Figure 32, Production rate per hour during week 41. The data was collected during Monday, Tuesday, Wednesday and Friday. The average production rate was 73 products per hour. (During Thursday this week there was no production)

Figure 32 shows the actual production rate measured each hour during daytime week 41. One of the days, Thursday, did not have any production. The average production rate was 73 products per hour.

5.6 Second Test Scenario: AGV-system with no speed change 1.0 m/s.

The objective of this scenario was to study the AGV-system without any speed change. The results were also used as reference to following case studies. Figure 33 shows the output for an increasing number of AGVs. The output of the system do increase until the added AGVs becomes too many and cause congestions which decrease the performance. AGV-system fleet-sizes of 24 to 35 AGVs have been tested.

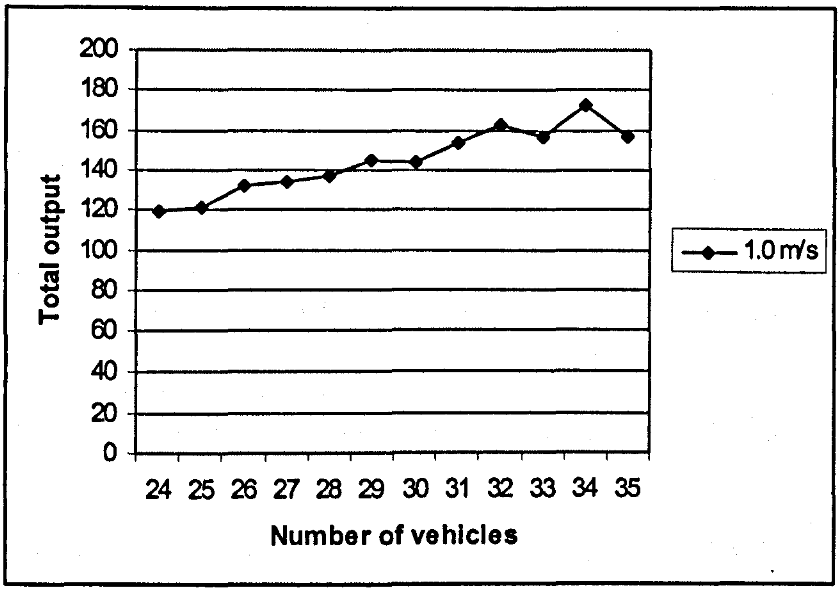

Figure 33, Output for maximum speed of 1.0 m/s. The diagram shows an increased output for an increasing number of vehicles, though the increase apparently stops at around 165 products.

The speed of the vehicles is either 1.0 operating on normal straight-line segments, or 0.6 while traversing curved segments, if they are not accelerating or decelerating between the different segment configurations, or to standstill. Figure 34 shows the average time spent in different states for AGVS configurations with varying number of AGVs. In the diagram in Figure 34 the loading and unloading of pallet states are not included since these are constant for each pallet moved. Most time is spent for empty travel and it can be assumed that since all AGVs are busy most of the time, an increase of the AGV-fleet to more than 35 vehicles will increase output even more.

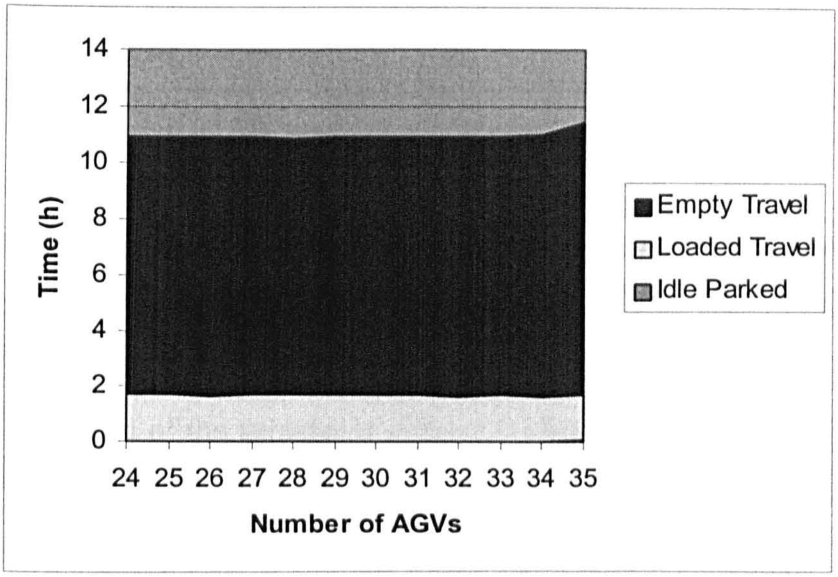

Figure 34, Time spent in different states for the AGVs. The diagram shows the average time that the AGVs have spent for empty travel, loaded travel, or idle parked. The last state can be seen to occur for 35 AGVs for a very brief time. The AGV-system is busy mostly in a state of empty travel. The time for empty travel increase for 35 AGVs and more. Time spent for loading and unloading pallets are not included since they are constant for every load-transfer.

This is however a complicated problem since the presence of numerous buffers add dynamic properties to the system which are difficult to predict. The number of blockings also increases for more vehicles. These two aspects can explain the trend of the curve in Figure 33 for varying numbers of AGVs where a higher AGV-fleet configuration can result in a lower output.

5.7 Third Test Scenario: AGV-Systems with maximum speed of 1.1 m/s to 1.3 m/s

The objective of this scenario was to study the performance for a guide-path layout with a maximum speed of 1.1 m/s at high speed sections. These sections are characterised as long, straight, and without any crossings, to motivate the higher speed. AGV-system fleet-sizes of 24 to 35 AGVs have been tested. The output is measured over three days of production.

The speed of the vehicles is either 1.0 operating on normal straight-line segments, 0.6 while traversing curved segments, or above 1.0 m/s if on a high-speed segment, if they are not accelerating or decelerating between the different segment configurations, or to standstill.

In Figure 35 it can bee seen how the output of the production line seem to reach a maximum for 34 vehicles. This trend is clear also for the speed-tests from 1.2 and 1.3 m/s in Figures 36 and 37.

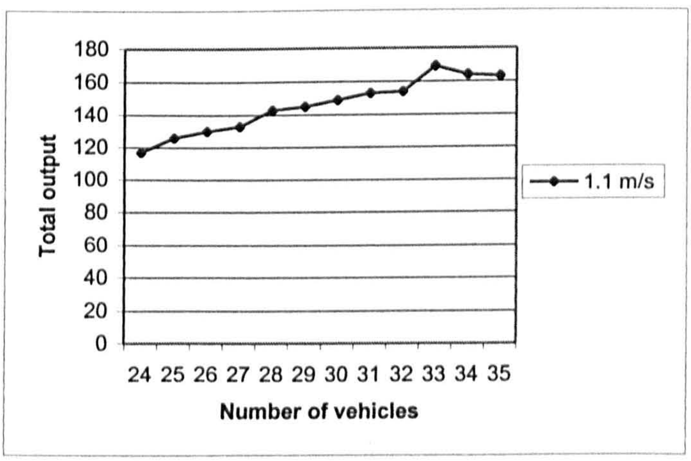

Figure 35. Output for maximum speed of 1.1 m/s. The output of the line is shown for different numbers of vehicles. The maximum speed of the high-speed sections is 1.1 m/s and the normal speed is 1.0 m/s.

Increasing the fleet size above 35 vehicles does not improve the output. A comparison between the different speed configurations shows little difference for the same AGV-fleet size. It can be concluded that increasing the speed is according to these results not improving the performance.

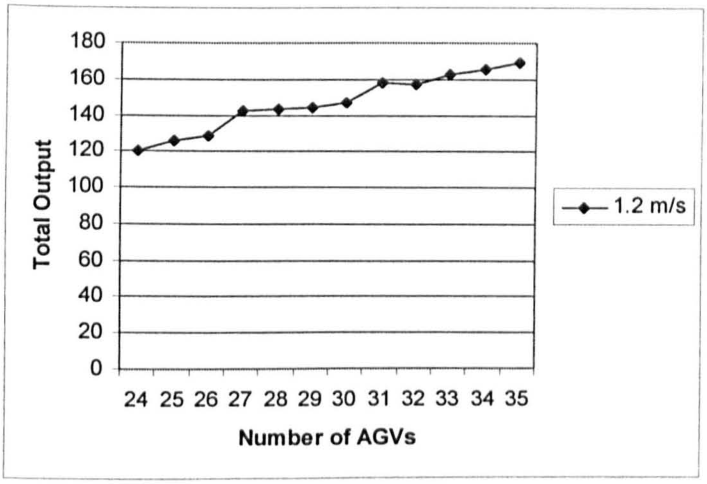

Figure 36, Output for maximum speed of 1.2 m/s. The output of the line is shown for different numbers of vehicles. The maximum speed of the high-speed sections is 1.2 m/s and the normal speed is 1.0 m/s.

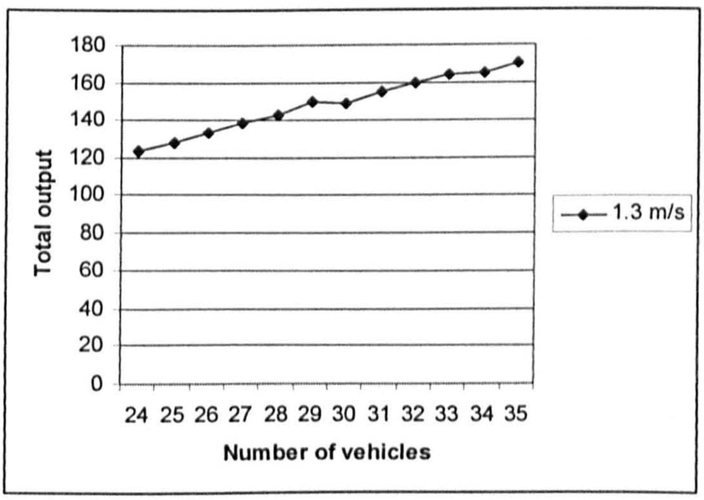

Figure 37, Output for maximum speed of 1.3 m/s. The output of the line is shown for different numbers of vehicles. The maximum speed of the high-speed sections is 1.3 m/s and the normal speed is 1.0 m/s.

5.7.1 Velocity considerations of AGV-system design

The use of multi-speed AGVs is an interesting research issue as noted by Hoff and Sarker (1998). AGVs may then be used more effectively in larger facilities. However decision rules will have to be developed for these speeds, as well as analysis of their effect on dispatching and guide path methods.

Limitations in velocity are regulated by personnel safety regulations and material safety aspects as well as physical properties of the AGVs. The Swedish Work Safety Council recommends a maximum of 1 m/s (metre per second) for AGVs. It can however be argued that with sufficient safety equipment and on-board sensing capabilities AGVs can travel safely at higher speeds than this. This can obviously lead to an increased cost for the AGV-system. One of the secondary objectives of this study is to rephrase the question, instead of focusing on the cost-side, how much more expensive will the system be, focus is changed to how much can be gained by increasing velocity? This is an essential issue for the use of modern 3D simulation tools because both the evaluation of potential benefits and the development and evaluation of an actual design can be considerably supported by simulation tools. In the case of this AGV-study the use of additional sensing capabilities for an AGV is evaluated in a large-scale system by motivating an increase in velocity. In the next chapter the same sensing capabilities are evaluated on a vehicle control level. A summary of the scenarios is shown in Table 4.

5.8 Fourth Test Scenario: Change in Workcell Shipping Logic

One of the objectives with the simulation of the J-division was to study the possible improvements that could come from changing the logic of the overhead gantry in the workcells. The logic used today was programmed during the system introduction in 1988 and was never questioned due to over-capacity in the plant. Today when there is a need of increasing the throughput the system design is questioned and scrutinised.

The present logic blocks pallets with 19 processed crankshafts until a new unprocessed pallet arrives to the cell. This is done by keeping the last part of the pallet in one of the machines and not removing it until a new part can be fed to the machine. First after this the pallet is completed and released for the downstream cells. The new logic would release the last processed part whether a new pallet has arrived or not, making the processed pallet available for the downstream cell.

The result of such a change is unknown and a study of potential improvements was needed. The simulation model uses the full set of external buffers and is identical to the original model in data and configuration, with the only difference of the cell logic. Ten batches are used in the simulation based on week 41. This configuration makes the run identical, apart from the cell logic. This provides a good experiment set-up for comparison.

The results from the run where at first surprising, the expectation was that this change would improve the throughput of the plant. Instead the simulation showed that the throughput remained unchanged. The same random seed was used and the results from this simulation compared with the first scenario are identical.

The difference with the new logic is a decrease in work-in-process. The new logic lowers the WIP value with approximately 120 - 200 parts, which is a considerable amount of capital, unnecessary located in production. These results are reasonable, if each workcells under some circumstances unnecessarily holds a pallet the number of parts in production are increased. If ten of the 32 workcells are in this state WIP is increased by 200 parts.

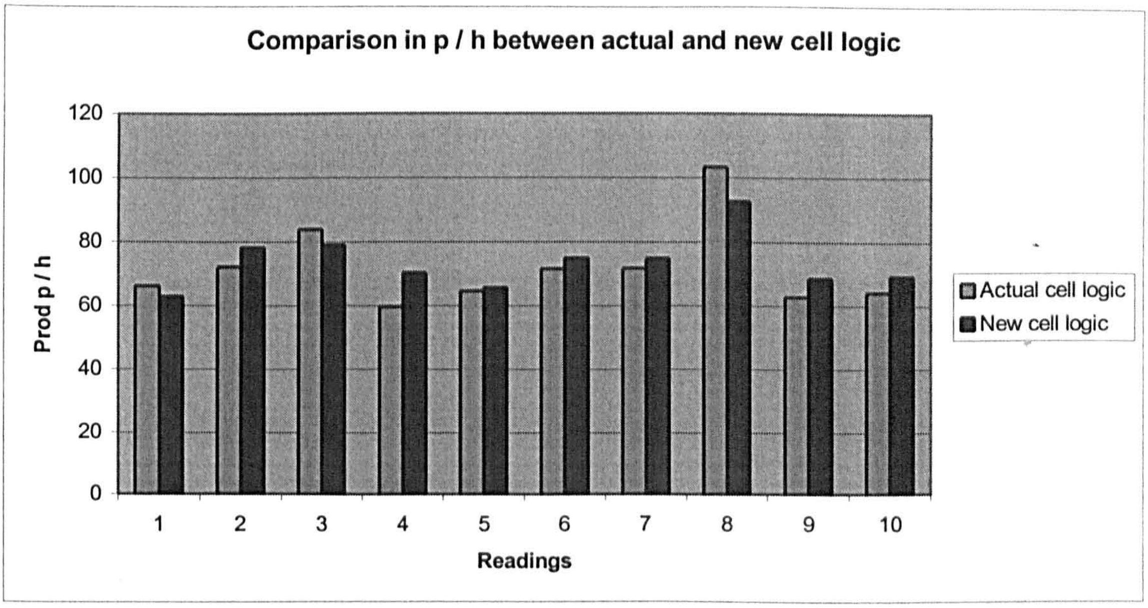

Figure 38, Comparison between production rate in parts per hour (p/h) for present and new workcell logic.

Since the new logic does not improve the bottleneck of the system the throughput remains the same. So the change in logic should not improve the flow through the bottleneck and as a consequence the throughput is not improved.

This logic does indirectly confirm another question that arose during the modelling phase. Will the assumption of substituting the real AGV-system by the default controller in Quest make any differences in the simulation and the results? It would if the bottleneck was the AGV-system, but this does not seem to be the case. The new logic makes the pallets go faster to the next downstream cell, improving the possibilities for the AGV-system to cope with the demand from the cells. If the AGV-system was the bottleneck then the simulation would show a clear improvement in throughput between the two different cases. This was not the case. If in the future the cell times are decreased then the AGV-system could still become a bottleneck factor.

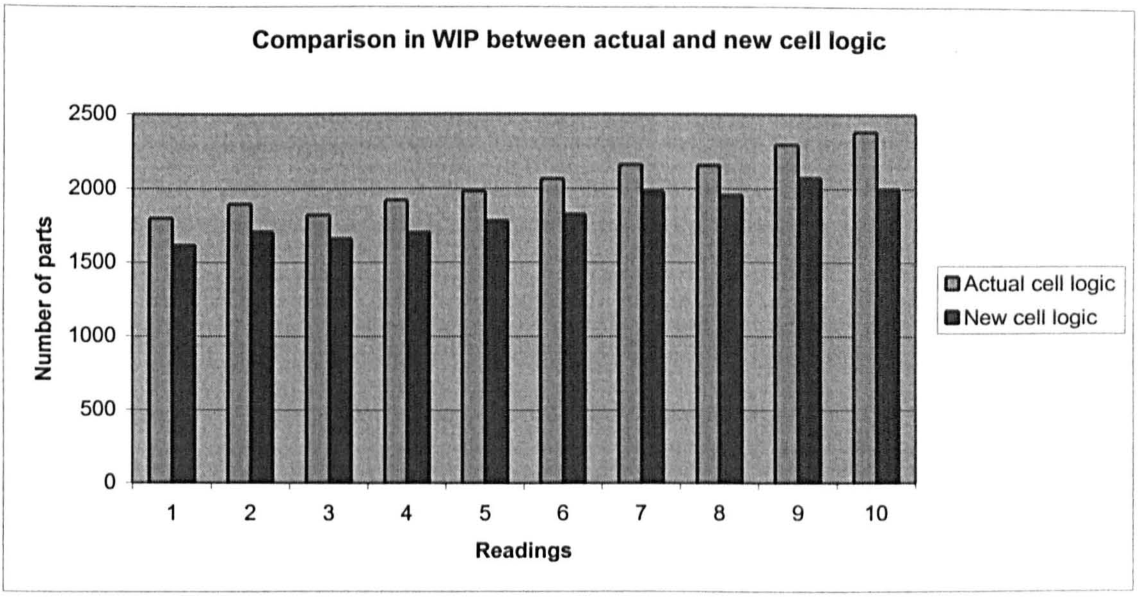

Figure 39, Comparison between WIP-values for present and new logic.

5.9 Conclusions

There is a strong correlation between the other workcells and the AGV-systems. In this case the performance analysis of the AGV-system will not be more accurate than the combined accuracy of the AGV-system model and the workcell-models.

One of the objectives was to identify the bottleneck of the system, either the AGVS or the workcells. The bottleneck was identified to be a workcell but which workcell changed depending on the circumstances. An investigation was carried for scenarios where vehicles traversed high speed section. The results of this showed little increase in overall productivity. The simulation study showed however the advantage of undertaking a detailed simulation of the AGVS together with the production system. Both these systems should be modelled to some detail, since a very detailed AGVS-model co-operating with a low-detail production system model is not very reliable.

Conclusions about the production-system are:

- The simulation model has the potential to simulate the present system and can be used for experiments.
- The system shows a sensitivity to set-ups. Productivity is rapidly decreasing with an increased number of set-ups.
- For batch sizes to be reduced a decrease in set-up time is necessary not to loose productivity. Smaller batches would lead to less stock.
- The bottleneck of the production line is non-static and depends on the circumstances. This makes the placement of additional buffer capacity upstreams from the bottleneck difficult.

Conclusions about the AGV-system are:

- The AGV-system does not affect the productivity of the production line in a negative manner. The results show that the bottlenecks are in the workcells and not in the AGV-system.
- Increasing the speed for certain sections of the guide-path layout only resulted in a small improvement of the throughput approximately 5 %. The high-speed sections were set to a maximum speed from 1.1 to 1.4 m/s. The rest of the layout had a maximum speed of 1.0 m/s. Little improvement were found for increasing maximum speed above 1.2 m/s. This can be explained by the length of the high-speed sections, which in few cases are long enough for acceleration and deceleration up to 1.4 m/s.
- The assumption that no blocking takes place strongly reduces the value of an analysis when studying this type of AGV-system. For detailed simulation analysis this assumption is unrealistic for other than very simple AGV-systems with few vehicles.
- The assumption of not considering the battery recharge process for AGVs can also be unrealistic since this process not only reduces productive time for the AGV-fleet but also increases the traffic intensity and can have an influence on

other design considerations as well. In this study the battery recharge process is not considered since it is assumed that production takes place during one work-shift only and that there is enough recharging points and time for recharging between work-shifts.

The requirements for AGV-development that can be concluded from this research study are:

To include a detailed simulation phase in an AGVS-development process should be valuable if:

i) The production system is large, (approximately more than five machines and five AGVs).

ii) Performance of the production system is difficult to predict due to failures, break-downs, untested technology, or the scheduling of limited resources.

iii) It is important to involve many people in the development process.

iv) There is little time for development and the process must not be delayed.

A simulation study of this size strongly motivates the use of a structured simulation methodology to produce an acceptable model.

An interesting aspect of the first research case at the Volvo Car Corporation Engine Plant is their AGV-systems. One AGVS was studied out of eight existing at the plant. To apply the detailed simulation approach proposed in this thesis to the whole plant would have been difficult considering the complexity. Modelling only one of the AGV-systems was considerable work and the simulation software had some problems handling the model.

6. Simulation in the Design of Semi-Autonomous Vehicles

The second research case is designed to approach the second and fourth objective of the thesis:

i) to study SAV-simulation and develop a virtual environment for SAVs which supports the development of novel functionality, and

ii) develop a unifying framework for the design process of AGV-systems. The work model will strongly benefit from an industrial simulation study that includes the development of a virtual environment for the design of novel functionality of AGVs. The location of the experiments were in an industrial lab at the machine vendor Euromation, Skövde, Sweden.

A full simulation environment was developed to support GEometry Simulation (GES) of AGVs by increasing the capability of a commercially available Computer Aided Robotics software (Cimstation 1996b). The features added were:

(i) Object-oriented generic SAV model.

(ii) Sensor simulation by collision detection of geometries.

(iii) Vehicle Control System emulation closely resembling the real SAV-application

The tests of the GES-environment versus the real SAV included:

- Simulation of main navigation technique with inductive sensor for wire-guidance
- Simulation of a Sick Laser-Range Scanner (LRS) and a feasibility study of the LRS for automatic unloading of lorries.

In section 6.6 a combined methodology is proposed which integrates the development of novel functions into a traditional AGV-design framework. The methodology includes simulation approaches and is based on a combined systems engineering and simulation methodology.

6.1 Introduction

A laboratory study was conducted to evaluate the use of continuous-path simulation in the design of novel AGVs, or specifically in this case Semi-autonomous Vehicles. The SAV concept has been developed during a EU-funded INCO/COPERNICUS project, and the research vehicle platform was developed by Euromation (Moore et. al. 1998). Several applications of the Euromation SAV has been delivered and are in operation in industry. The SAV-concept is described in section 2.3.4.

6.1.1 Objectives of Study

The main objective of the study was to present a methodology on simulation of AGV-systems, and as a part of this develop a method on simulation in the design of novel AGVs, specifically Semi-autonomous vehicles.

Specific sub-objectives are:

i) Identify factors and develop a virtual environment and a method for using simulation in the design of novel AGVs.

ii) Integrate the novel AGV simulation method in an AGV-system development context.

iii) Based on research studies presented in chapter 5 and this chapter propose a combined methodology for simulation in the design of AGV-systems.

Test Scenario	Description	Result
1	SAV Carrier Control System emulation	Off-line programming of vehicle possible
2	Simulation of SAV Wire-guidance	Validated, good resemblance with vehicle
3	Pre-conceptual study of automatic unloading of lorry	Concept feasible

Table 5, Test scenarios for simulation in AGV-design.

6.2 The Semiautonomous Vehicle Concept

The SAV concept of Euromation attempts to solve the problem of autonomy in industrial applications by explicitly controlling the level of autonomy at different occasions. A script command language has been developed which is used to instruct a vehicle what navigation method to use, when to allow obstacle avoidance etc.. If e. g. wire-guidance is used as the main navigation method, then some sections of the guide-path layout can have enough space for an obstacle avoiding motion to occur. These are then clearly stated in the command script of the vehicle. Some load-transfer points may be located away from the guidepath. These can be reached using dead reckoning as navigation method provided that the distance is not too long. Table 6 shows the script commands for such a case. Requirements for a simulation environment are to: i) simulate the sensor systems and navigation method or combination of methods used by the SAV, ii) emulate the script command language, iii) accommodate the evaluation of an SAV in its intended environment. In the following section an example AGVS application is presented to illustrate the potential use of a simulation environment.

1. DriveWireToDistance [% of Max. Speed] [Distance]
2. DriveFreeToDistance [% of Max. Speed] [angle of steering wheel] [Maximum distance]
(load transfer occurring at load transfer point)
3. DriveFreeToWire [% of Max. Speed] [Maximum distance]
4. DriveWireToDistance [% of Max. Speed] [Distance]

Table 6, Script command for an off-guidepath navigation. The first command drives the SAV in position for leaving the path. Then a free-moving motion is made to the load transfer point. Command three instructs the SAV to find the wire and resume guidepath navigation.

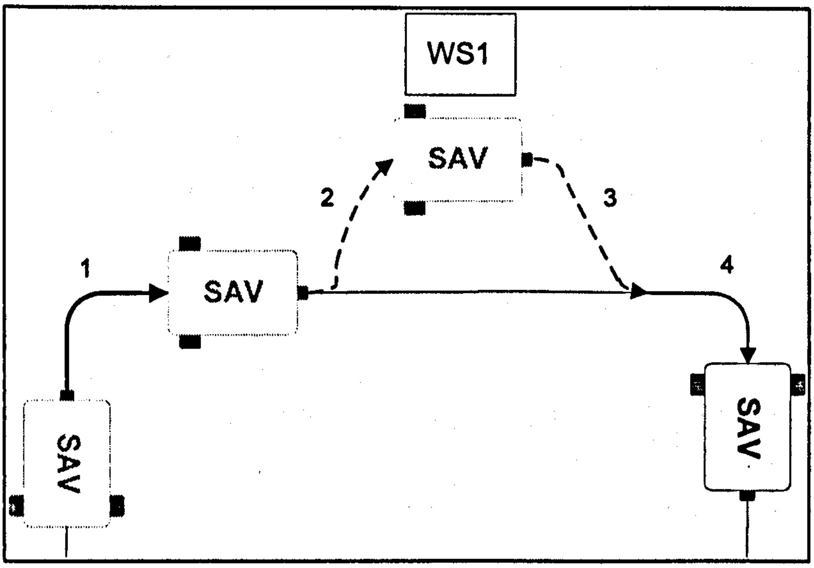

Figure 40, Example of off-guidepath navigation. The trajectory resulting from the SAV commands in table 6 is showed. Section 1 and 4 are wire-guided commands and section 2 and 3 are free-moving commands.

An example application for an AGVS is: for a manufacturing plant an AGVS is used for materials handling. The main navigation method for the AGVs is NDCs Laserway-concept which mimic a wire-guide-path but without the physical path. A virtual guidepath is used and programming is achieved by manually moving the AGV along its intended path. Positioning is achieved by means of triangulation by a vehicle-based laser scanner that locates landmarks (reflecting tabs on the walls) (NDC 2000).

In some areas of the plant the Laserway system is, according to experience, likely to fail due to unwanted reflexes from shiny surfaces on machines. In these areas dead reckoning is a potential navigation method option for the AGVS. In other areas of the plant where the AGVS must operate there are long corridors with windows. The Laserway system is also in this case likely to fail due to problems of locating the reflecting tabs in the right positions. A possible navigation method here would be to use a wall-following algorithm using data from the laser-range scanner located 10 cm above floor level on the AGV.

A conceptual study needs to be undertaken regarding the novel navigation methods, the combined use of these, and the transition from one method to another. Also a framework of the script command language is needed with possible extensions to support the suggested navigation system. When the feasibility of this navigation approach is established, it is also of interest to evaluate the whole manufacturing system performance using the specified AGV-system.

This is likely to require two types of simulation environments, firstly a vehicle focused approach, which supports emulation of control, simulation of sensors, and kinematical models of the AGVs, and secondly an environment that focus on the flow of material and not on the technical details of how the MHS operates. Since the MHS is such an integral part of a production system, an evaluation only focusing on one part is very likely to miss dynamic interaction aspects between the MHS and the manufacturing system. The second environment must support the analysis of interaction between the MHS and the manufacturing system in terms of machines, buffers, and operators etc. for the study to be realistic.

This second environment can however not evaluate the technical feasibility of a navigation method approach, but must assume a certain behaviour regarding availability, functionality etc.. What it can do is to test the potential advantage or value of implementing a novel function of an MHS. Such a function must in the end improve the MHS performance in some way, preferably to a higher value than the cost increase of the function.

An additional note on the navigation problems presented is that they can presumably be solved in other ways and the Laserway could be used as the only navigation system without any costly additional systems. However, its disadvantage is its very strict guide-path layout, although virtual. Flexibility is provided by means of reprogramming but not by allowing "flexibility while in operation". The suggested alternative navigation methods in this example can provide other types of flexibility and functionality e. g. intelligent decision making as obstacle avoidance. This requires more information about the environment and thus additional sensors. The implications on the virtual environment are thus still valid.

6.2.1 A novel control architecture for SAVs

The work presented in this section is a part of the results from an INCO/Copernicus project. MSTU Baumann, DMU, and Euromation have carried out the work. These results were presented as a deliverable to the project (Lakota et. al. 1999).

This novel control architecture illustrates well the potential of the SAV-concept and also the value of a virtual environment that can accommodate novel function development for AGVs.

The control architecture of the Euromation Semi-autonomous vehicles initial control system is the Carrier Control System (CCS). It provides predefined command-based motion control and in the initial configuration the laser range scanner is only used for safety purposes to prevent collisions. The novel Intelligent Control Layer (ICL) supplements the CCS providing the AGV with capabilities to navigate autonomously around an obstacle or between obstacles to reach a target position. The tasks that it solves are: i) vehicle localisation (determine current position), ii) map building (obstacle detection and creation of environment model) and, iii) local navigation (planning and moving along alternative trajectory).

6.3 A Simulation Environment for novel AGV design

With a starting point in one of the computer aided robotics tools available (SILMA 1996a), an environment for novel AGV design, or SAV, was developed.

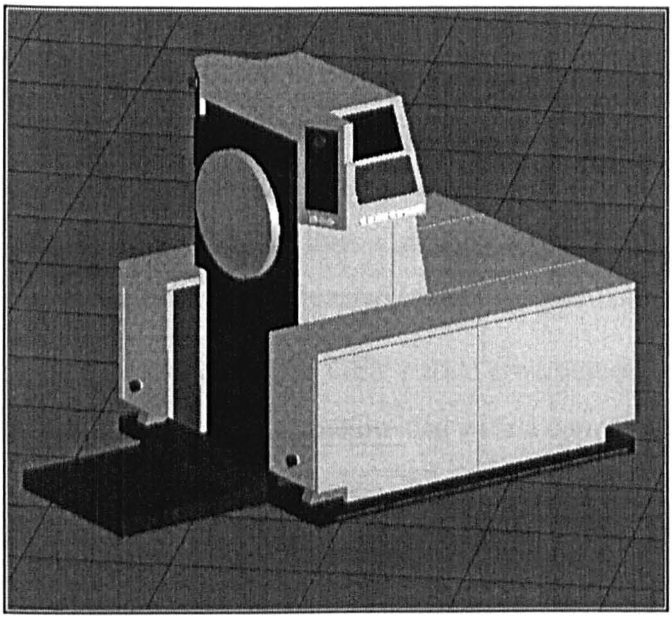

Figure 41, A model of the Assembly Carrier SAV. The geometrical representation of the vehicle is nominal from drawings and the control system, including the sensors, are emulated. This model is developed in the GES-system Cimstation. The real vehicle is shown in Figure 14, chapter 2.

The environment was realised in a Computer Aided Robotics-simulation software. It is worth mentioning that this virtual environment supports the design and evaluation of an SAV, its navigational capabilities, programming commands, but it does not support the evaluation from a system perspective with several vehicles performing an MHS task. The virtual environment is very useful for developing vehicles for many purposes but there is also a great value in estimating and evaluating the performance of the whole SAV (or AGV) system in its intended environment. The average size of and AGV-system varies, but a the average fleet-size of AGV-systems sold in Japan was approximately 2, and in USA the size was 5 AGVs (Ward 2001). For some applications the AGV-fleet size will be considerably larger than this, which increase their complexity. For a simulation framework to fully support the development of Semi-autonomous vehicles in an AGV-system context, both the system perspective and the single vehicle perspective must be considered. The requirements of the system perspective were identified in the first research case in chapter 5, Identification of Factors for Industrial AGVS Simulation.

There is a considerable difference between the two software types DES and GES. The previou type which is discrete event supports the modelling of production systems e. g. machines, operators, MHS, scheduling of resources, etc.. Geometry simulation to which category CAR-systems belong, focus on a detailed technical level. To arrive at a simulation framework that supports SAV development both software types are necessary. Based on this a methodology is proposed to cover most of the design considerations. It is presented in section 6.5.

The requirements of the GES virtual environment were to:

- Include sensor simulation also with a component library of sensors.
- Include component library AGV parts.
- Mimic the Carrier Control System of the research SAV.
- Support the development of novel navigation algorithms e. g. pre-emptive learning of ANNs for obstacle avoidance, or wall-following.
- Provide a high degree of accuracy of geometry representation of the SAV and for its environment.

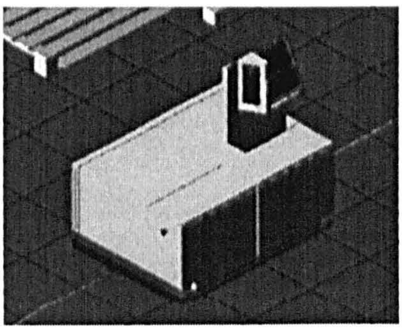

Figure 42, A model of the small SAV used for experiments. Note that there is no load handling device. This vehicle configuration is also smaller than the assembly carrier. The same drive and control system is used but with less battery capacity. This research vehicle and the assembly carrier illustrate well the modularity concept of the SAV, which also includes modularity of the sensory systems.

6.4 Simulation of SAV wire-guidance

The aim of this study is to simulate the wire-guidance operation of a Euromation SAV. The virtual environment presented in this chapter is an important part of the development of novel functionality which plays an important role in the simulation framework. Wire-guidance is commonly used and makes a good test case for both sensor simulation and simulation of SAV-operation.

The Carrier Control System (CCS) was integrated with the wire-guidance sensor model and the vehicle operation showed a very good resemblance with real SAV.

6.4.1 Sensor simulation of Wire-guidance Sensor

The principal method of wire-guidance is to let an alternating current run through a wire so that the magnetic field around the wire can be detected by a coil-arrangement. By measuring the induced voltage over the coils, the distance to the wire can be estimated. Several frequencies are commonly used so that the AGV can distinguish between different paths, e. g. in a crossing (Everett 1995).

A high-frequency signal can also be fed to the wires to communicate with the AGVs. Figure 43 shows a theoretical model of the wire-guidance antenna used by Euromation in the SAVs.

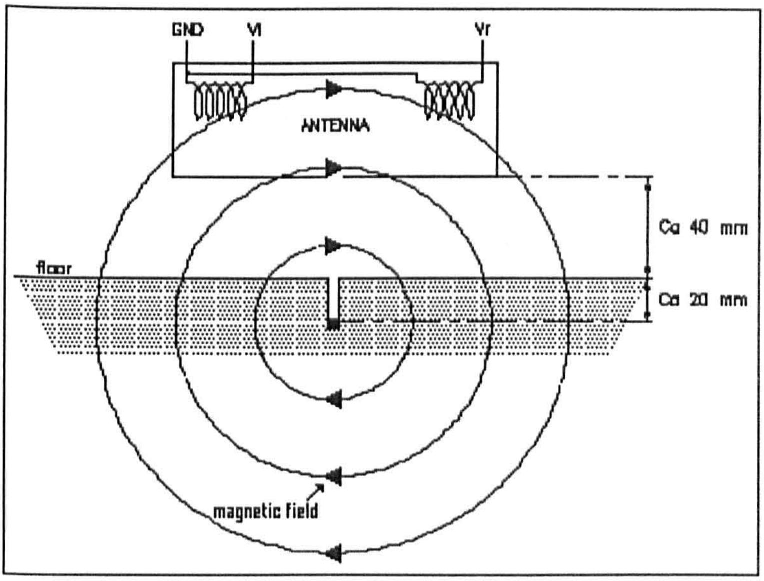

Figure 43, Theoretical model of wire-guidance antenna. Two coils are used as sensors in a closed control loop with the drive and steering system. The difference in induced voltage between the coils is the signal parameter. The simulation sensor model mimics this behavior by first colliding a rectangle in the plane of the figure with the wire, and then measuring the perpendicular distance between the coils and the wire.

The generic sensor simulation model proposed by Eriksson and Moore (1995) was used to model the wire-guidance antenna, see section 3.4.2. The sensor body is represented by a box and two cylinders represent the coils, see Figure 44. The wire-guidance antenna is firmly mounted on the axis of the steering wheel and moves with its motion. The sensor model was developed to mimic the operation of the wire-guidance antenna.

Each coil receives a distance estimate based on the collision between the detecting volume, or plane which is vertical and perpendicular to the wire-path, and the wire-path. If no collision occur no output is provided from the sensor model. The sensor model output also resembles the real sensors update frequency. This provides an event-based model which reacts on the distance to the wire, which is important to mimic the wire-guidance related commands that the SAV can perform.

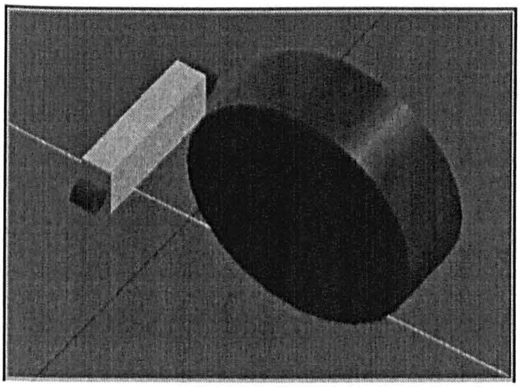

Figure 44, Simulation model of wireguidance sensor. The sensor is situated in position in front of the front wheel, and moves with the steering motion. The two coils can be seen on both sides of the sensor and a plane represents the detection range. The plane is positioned so that it collides with the wire.

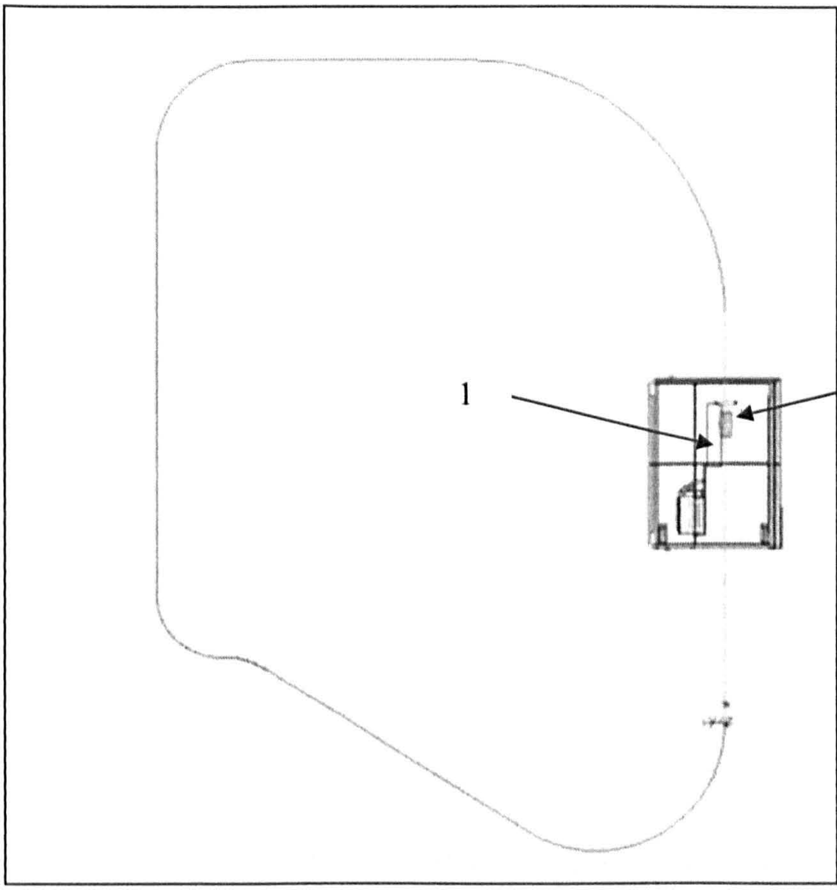

Figure 45, A model of the SAV laboratory environment. The SAV is in start position to the right, shown in wire-frame mode. Underneath the vehicle an elongated steel plate can be seen just next to the guide-wire (1). This plate is a landmark defining the starting position and is used by the SAV for reference. The different colour of the 'active' guide-wire section under the SAV indicates that the sensor simulation is active and the SAV is on the path. The wire-antenna and the front wheel are at (2).

The control loop of the SAV was emulated when in wire-guidance mode. The control-loop included the wire-guidance model, the control system emulator, and the drive and steering wheel actuator. The wire-guidance model sends a reading to the control system at a certain update rate, which contained information about the distance and direction to the wire.

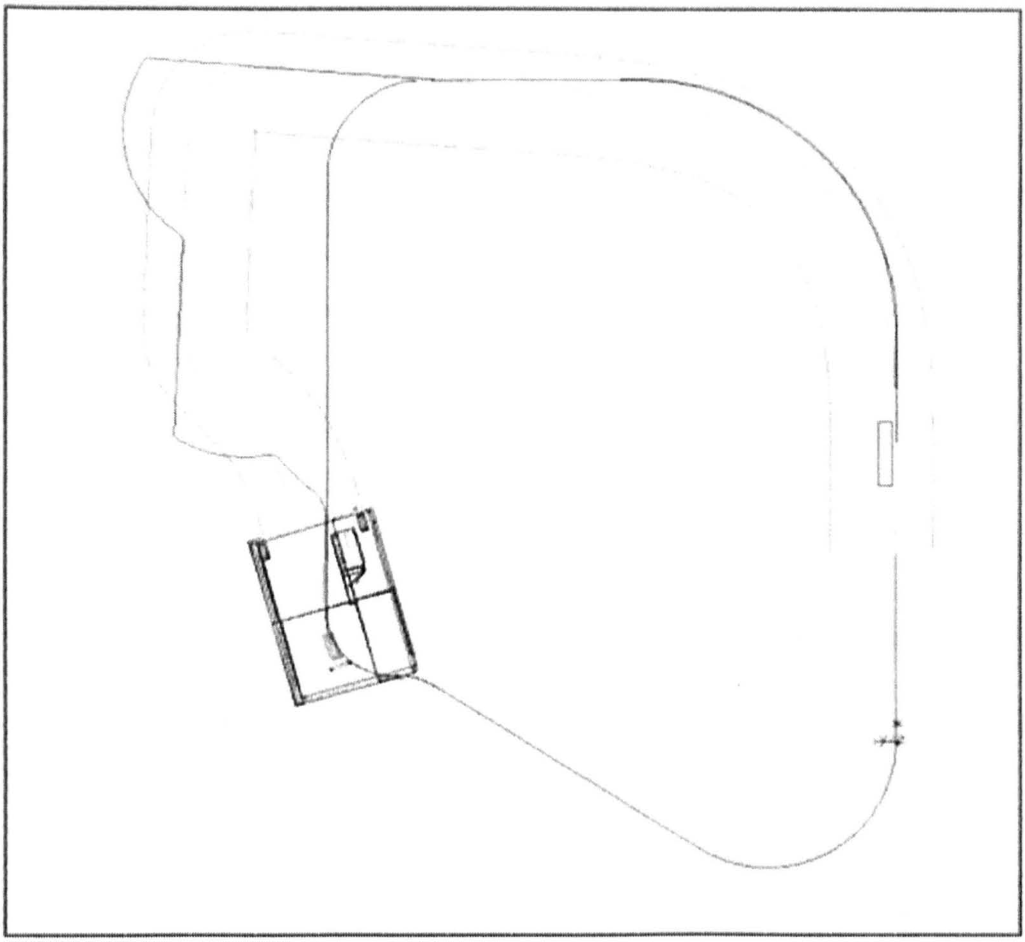

Figure 46, Trajectory of SAV. The SAV started at the start plate to the right in the picture, drove in wire-guidance mode, left the wire-path in the upper left of the picture, and executed drive-free commands, and went back to the wire-path at the end-position.

The control system emulator is in wire-guidance mode equivalent to an adaptive PID-regulator, just like the real control system. The PID settings are different depending on the present angle of the steering wheel. A high proportional factor is necessary not to loose the wire when it makes a turn. The higher the wheel angle the higher the proportional factor must be. When driving straight forward the proportional factor must be low to avoid nervousness of the system resulting in a twitching motion. Instead the integrating factor must be relatively high to decrease the position error lateral to the wire. The PID settings of the real controller were used after some modifications. The actuator model of the SAV updates the position of the wheel with a certain delay.

Several runs were made with varying settings. The speed was increased above 1.0 m/s, which resulted in the SAV loosing the wire in the right upper corner.

During some of these runs, the SAV did not straighten out enough after the first left turn, see figure 46, which resulted in the vehicle not finding the wire after performing the free-move commands. The simulation runs showed that the position error of the vehicle relative the wire was varying which resulted in a varying start position of the free-move commands. Also the influence of the vehicle speed on the position error was possible to simulate. For higher speeds the result was that the SAV 'lost' the wire, i. e. the wire-sensor came to far from the wire as the steering actuator did not update the wheel position fast enough, which caused the vehicle to stop.

6.5 Pre-conceptual study of Automatic Unloading of Lorry

A pre-conceptual study is presented on the development of an innovative SAV functionality, the automatic unloading of lorries with palletised loads.

The objective is to identify factors for simulation in a single-vehicle perspective, and to provide input to a conceptual and detailed simulation study from an AGV-system perspective.

The study is entirely simulation-based and no experiments have been undertaken using real SAVs. The background to this study is ideas of extending the use of the SICK laser range scanner (LRS) which is presently used for safety purposes only, i. e. to detect obstacles within a defined warning zone and an emergency stop zone ahead of the SAV. A simulation model of the LRS has been developed and tested successfully to well mimic the real sensor.

The task of unloading a lorry requires several capabilities of the SAV:

- Navigation not relying on a guide-path.
- Localisation of pallets, both position and orientation.
- Load handling device for lifting the pallet (a fork lift).

Several other aspects needs to be addressed e. g. physical conditions of floor in the lorry, and in the docking bay, how the SAV will traverse onto the lorry, but also control issues are of interest. The objective of this study was however to identify the potential of this functionality, e. g. will it require a larger AGV-fleet size. The potential benefits are significant in terms of reduced buffers and WIP, and other advantages of a Just-In-Time approach. Figure 47 shows the structure and timing of the unloading function of the SAV.

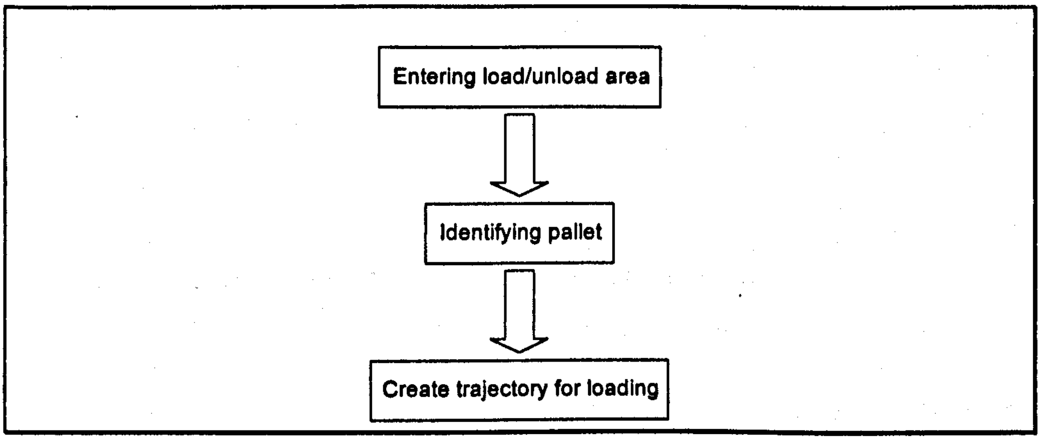

Figure 47, Steps in the automatic unloading of pallets. An example of local navigation is presented. The first step includes leaving the guidepath, in the second step the position and orientation of a pallet is made, with knowledge about the vehicle and the pallet location a trajectory is created. For the suggested SAV configuration, see Figure 21, the SAV will have to reverse to load the pallet.

The required work steps for the conceptual simulation study that needs to be made for this development are:

1. Make models of SAV with forklift configuration.
2. Make model of the environment including docking bay, and lorry.

3. Develop navigation algorithm that performs pallet localisation.
4. Develop navigation algorithm that creates trajectory for loading the pallet.
5. Test and evaluate algorithm.

Steps one to three should cause few problems. The third step should be quite feasible since the sensor algorithm identifies the three wooden supporting pieces of the pallet, when viewed from the correct side, and calculates there position and orientation relative to the SAV. The fourth step should also be feasible since the SAV can navigate locally with a high accuracy using dead-reckoning. This requires the SAV to reverse, turn and then while reversing place the forks in position for loading the pallet. The fifth step is of no problem since both the SAV, the sensor model, and very similar environments have been evaluated in using the virtual environment, e. g. the wire-guidance simulation in section 6.4.

In the next section the LRS simulation model is presented to illustrate the simulation of this pre-conceptual study.

6.5.1 Sensor Simulation of Laser Range Scanner sensor

A sensor model of the SICK PLS (SICK 2002) was developed and evaluated using the virtual environment for single vehicle simulation.

Figure 48 shows the simulation model of the LRS, and how it detects a pallet. A generic sensor model is used to mimic the behaviour of the real sensor (Eriksson and Moore 1995). The information of the LRS is updated every 80 millisecond, however the transfer rate becomes lower because of a RS232 connection between the sensor and the control system of the SAV. The safety function of the system is hardwired using separate signals.

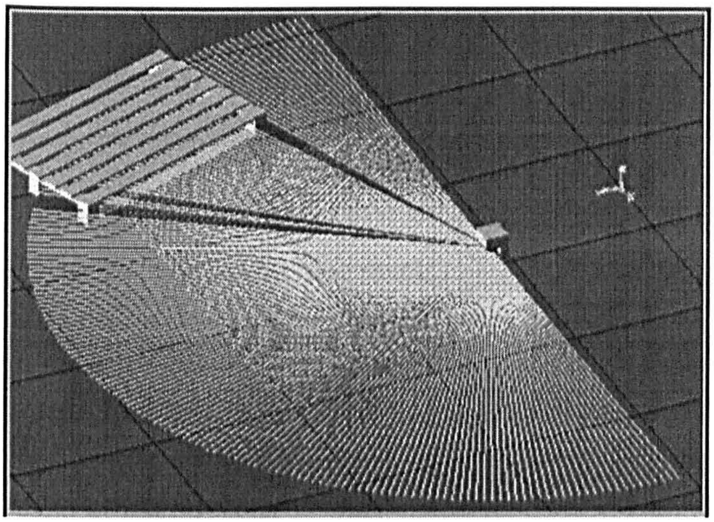

Figure 48, Sensor simulation model of the laser range scanner SICK. The sensor body is to the right with 181 trace-lines, one for each degree of half a circle, representing the accuracy of the LRS. The collision detection function is active and trace-lines colliding with obstacles turn red. To decrease computational complexity and avoid an extensive number of collisions, the trace-lines are only three metres long. The real sensor is capable of detecting object up to 80 metres. The red and yellow field represent a warning and an emergency stop area respectively. If there are objects in this area the sensor sends an interrupt signal.

The LRS-model has been tested when integrated with a wall-following algorithm, showing good results. For lower speeds and with a well-defined wall (few items cluttering the wall) the functionality worked as intended.

6.5.2 Results and discussion

These initial SAV simulation test cases show the feasibility to evaluate and to some extent develop navigation functionality. Several sensor models can be used, one by one or concurrently to navigate the vehicle. Navigation algorithms that are frequently used in mobile robotics applications (Uhlin and Johansson 1996), e. g. wall-following behaviours can be developed and trained in the simulation environment.

A framework of an SAV with the Carrier Control System and script commands were developed, and the proposed virtual environment, AGV functionality can be developed in a structured and realistic way:

- The operational characteristics of navigation algorithms can be investigated and used within their limits, e. g. how robust a wall-following algorithm is to objects that clutter the wall.
- Navigation techniques that are not robust enough to be the main navigation technique can be used as a complement.
- Concurrent navigation techniques can be developed
- Material handling equipment can be evaluated in aspects of reachability, collision hazards with other objects when the mechanical devices are in certain positions, etc..
- AGV-system applications for non-existing environments can be developed.

Single-load and dual load vehicles and AGV-systems based on these respectively can not be easily compared in a straightforward way. Single-load vehicles tend to cause a higher level of congestion with more blockings due to larger AGV-fleet size. Dual or multiple-loading AGVs are more efficient but at the cost of a more complex AGV-system control. The risk of a deadlock can become higher as discussed in section 2.2.10.

Factors that need careful consideration are: i) what dead-locks can occur, ii) how and when will traffic congestion occur, iii) under which condition will planned control algorithms operate well, iv) what type of load handler is necessary and cost-effective.

Another controversy between the choices of technologies is wire-guidance navigation or landmark based navigation of Laserway type. This is a matter of cost compared to flexibility. Is a complex laser-based navigation with more possible programmable routes that can decrease the travel distance more cost-effective? Or is a wire-path based navigation combined with local free-moving navigation sufficient?

6.6 A Methodology for AGV System Design

In this section a methodology is proposed for the structured development of AGV-systems using simulation, including novel functionality development.

Using detailed simulation during an AGVS development project is a balance between the potential benefits and the cost of the study. If the type of AGVS is well known and thoroughly tested with few variants and uncertainties about the system, the simulation study can be unnecessary considering the extra cost and possible delay of the project. However, detailed simulation of a planned AGV-system is more relevant if the system is to include novel features with a less hierarchical and rigid control structure that has not been thoroughly tested. This is also the case if there is little knowledge and experience of the type of technology, and it has many possible configurations and variations. It can also be of interest to test and evaluate the function of individual parts of equipment as well as the AGV-system performance in its material handling context. Little work has been reported in this area, though much work has been done in both manufacturing system simulation and AGVS-development.

In the following section an introduction is given followed by the requirements for the methodology. Secondly the proposed methodology is presented in section 6.6.2. The methodology is finally evaluated in chapter seven.

6.6.1 Background

There exist many analytical approaches to AGV-system design. Many of these have been described in chapter 2 and they lack in terms of accuracy for the detailed design phase. Most methods and approaches presented have their focus in the conceptual phase and there is consequently a lack in the detailed design and evaluation phase. A summary of the design issues has been presented in the modified taxonomy of design and scheduling for AGVs. To summarise the best approach from the literature review, i) mathematical and heuristics methods should be used in the early conceptual design phase to decrease the solution space, and if possible find an optimal design, ii) simulation should be used to finalise the design and to test and evaluate it.

The development of control systems is needed to take advantage of the flexibility of free-path AGVS (Kim and Tanchoco 1990). Control architectures for AGVS can be from strictly hierarchical to completely heterarchical, and hybrid methods in between. Most of the existing AGVS operate under hierarchical control architecture. This also influences much of the research on AGVS design and the use of simulation in the development process. Novel navigation techniques that are increasingly being used in manufacturing environments place even more emphasis on the design methodology of AGV-systems to make use of their full capability.

Several sources have been used for the development of the methodology for AGVS design. Four main areas have been of interest:

i) Simulation methodologies for manufacturing system development, presented in chapter 3.
ii) AGV-system design methodologies, presented in chapter 2.
iii) Industrial AGV simulation, the first research case presented in chapter 5.
iv) Semi-autonomous Vehicle simulation, the second research case presented in sections 6.1 to 6.5.

Simulation specific methodologies that were found in the literature are:

- Strategic methodology of simulation in the production system life-cycle by Kosturiak and Gregor (1999), described in 3.2.
- The VSOP-model (Visualisation, Simulation, Off-line programming, and Production) of product and production development (Bolmsjö and Gustafsson 1998).
- Applied simulation methodologies for Geometry simulation by Banks (1998), and for Discrete-event simulation by Law and Kelton (2000), both described in section 3.4.1.
- Sensor simulation in GES-systems by Eriksson and Moore (1995)

Methodologies relating to AGV-system development found in the literature are:

- Detailed taxonomy by Ülgen and Kedia (1990)
- A number of approaches to some of the considerations of an AGV-system, e. g. guide-path layouts, load-dispatching rules, location of load and delivery points, idle vehicle policy, etc.. These are summarized in section 2.4.

The simulation methodologies are general to most production engineering problems, but they do not fully support the complex design issues of AGV-system design. Kosturiak and Gregor suggest the use of simulation for both strategic and operational manufacturing problems. They also advocate a continuous development of the simulation model during the design phase, starting from a conceptual level and continuing to a detailed level.

The methodology proposed in this chapter identifies several important factors of such simulation systems, and how they can be applied to novel AGV-system design.

6.6.2 Requirements of a Simulation based AGV-system Development Methodology

Traditionally AGV-simulation has been almost equivalent with discrete event simulation from a system perspective, as the research review indicates (see appendix 1). This is however not sufficient for novel AGV- development, e. g. SAV-systems. The advantages of applying GES-tools for the SAV-design can be significant.

The conclusion is to use a combined approach of both perspectives and both simulation software types. The requirements on a simulation approach from a system perspective were identified in the first research case in chapter 5, Identification of Factors for Industrial AGVS Simulation. Following that a framework of an SAV with the Carrier Control System and script commands were developed, and in the proposed virtual environment, AGV functionality can be developed in a structured and realistic way.

The requirements are:

- Technical and performance data on vehicle systems e. g. sensors must be available or possible to estimate, e. g. speed, acceleration, turning radius etc..
- Input to the simulation:

  i) conceptual data on the AGV-system configuration

  ii) the vehicle configurations e. g. sensory systems, drive and steering system, control system, and load handling system

Using detailed simulation during an AGVS development project is a balance between the potential benefits and the cost of the study. If the type of AGVS is well known and thoroughly tested with few variants and uncertainties about the system, the simulation study can be unnecessary considering the extra cost and possible delay of the project. However, detailed simulation of a planned AGV-system is more relevant if the system is to include novel features with a less hierarchical and rigid control structure that has not been thoroughly tested. This is also the case if there are little knowledge and experience of the type of technology, and it has many possible configurations and variations. It can also be of interest to test and evaluate the function of individual parts of equipment as well as the AGV-system performance in its material handling context. Little work has been reported in this area, though much work has been done in both manufacturing system simulation and AGVS-development.

6.6.3 Simulation in AGV-system design

Two main perspectives have been identified, the single vehicle perspective, and the AGV-system perspective. Both play an important role for the development of novel AGV-systems.

These are separated into two activities to enable the development of novel functionality. Table 7 shows the proposed methodology for AGVS development.

Simulation in AGV-system Design in its Whole Life cycle				Simulation Activity
Phase	**Single Vehicle Perspective**	**Flow of Information**	**AGV-system Perspective**	
Problem analysis and setting of goals	No simulation related activity			
Conceptual Design	Development of basic scenarios *-Vehicle type,* *-Equipment considerations,*	Functionality requirements Vehicle Performance	Basic model/scenarios development *-Facility considerations* *-Travel considerations* *-Schedule consideration* *-Main navigation method*	**Conceptual simulation model for comparison and evaluation of variants**
Detailed Design	Scenarios verified, if possible tested and evaluated *-Navigation methods,* *-Load handler system* *-Sensor systems* *-Control system*	Functionality requirements	Detailed design variables included, Verification, (validation) *-Path layout,* *-Vehicle dispatching* *-Control hierarchy* *-Flowpath type* *-Travel speed* *-Load / unload time*	**Detailed simulation model: material flow, control rules, production system**
System Installation	Simulation Aided Training	Simulated Running in-Personnel Preparation		**Simulation of system**
System Operation	Ongoing Improvement Process Testing of the Control Strategies Decision Support			**On-line simulation**

Table 7, Simulation in AGV-system design.

In the single vehicle perspective, the conceptual phase, a basic model is developed and from this several variants can be made for comparison of concepts. The second phase is the detailed design phase where customisation of the vehicle is made: i) mechanical structure, ii) load handler, iii) navigation functions, iv) sensory system, v) any special behaviour and functionality.

After verification and conclusion on the main concept or concepts, the system perspective can commence. Performance data from the single vehicle perspective is used, and a basic system level model is developed. Also here several variants can be made for comparison. The next phase is the detailed simulation where all relevant detailed considerations are included. Relevant aspects are those that can have a reasonably large influence on the AGV-system. The following aspects often need to be considered if not included:

i) Battery recharging, off production hours or during production

ii) Idle-vehicle location, should a parking location is to be used, or should idle vehicles continue moving on the guide-path.

iii) Presence of obstacles.

iv) Failure-data e. g. MTBD, MTTR, MDT for AGVs, machines, and other relevant equipment. Failures can be of several types:

   a) for machines e. g. seldom occurring large breakdowns with a long time to repair, and short but frequent corrections,

   b) for AGV-systems e. g. AGVs losing the guidepath, obstacles in the way, and free-moving AGV encountering problems in unstructured part of layout

The production system or systems performance is estimated regarding aspects as production output, product throughput time, work-in-progress, level of use of buffers, etc. for varying conditions. These conditions should be identified as early as possible in the design process. According to Law and Keltons method (se section 3.4.2) uncertain aspects and conditions that have an influence which is considerable on the key result variables should be studied carefully. Worst-case scenarios should be investigated to estimate the risk of combined worst case conditions and their effect on result variables.

Output from the simulation studies are used in the realisation phase in the form of input to mechanical design, electrical design, control system development and programming, education of personnel, and an evaluated design which reduces the risk of building problems into the AGV-system.

The main process of the development is the AGV-system perspective, which traditionally has been the main focus of research. Two possible main approaches can be identified: i) AGV-system development based on well-known technologies and concepts, and ii) AGV-system development including novel functionality aspects. For the first approach the AGV-system perspective is sufficient, since the information required for the analysis should be available. For the second approach additional information is necessary to base the final detailed design analysis on. This information is provided by the single vehicle perspective.

The information that is conveyed between the stages of development can be reversed, i. e. go from the system perspective to the single-vehicle perspective. Figure 49 presents a flowchart on the use of the methodology.

The two perspectives coincide well with the two types of simulation software, GES is focused on continuous processes, e. g. industrial robot motion and off-line programming, and DES is applied at a higher level of detail, e. g. flow of products through a production system. It would be unrealistic to apply the same level of detail of the singe vehicle perspective to the system perspective, e. g. ten vehicles using sensor simulation for several sensors running concurrently would require very much computing power. If even more aspects of the production system are to be modelled the level of abstraction must arguably be higher for the system perspective.

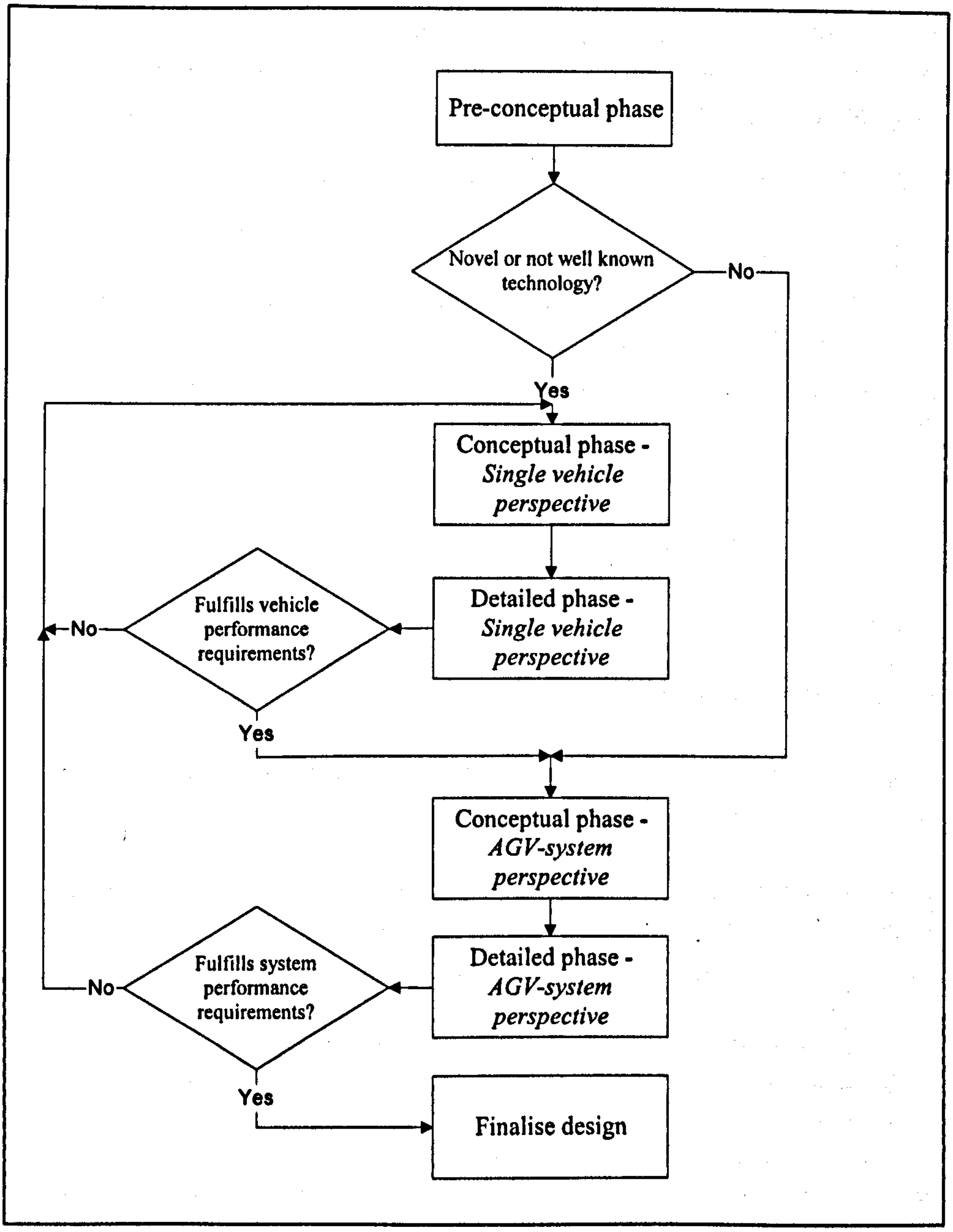

Figure 49, Steps in the AGV-system methodology.

There are several levels of adoption of the methodology that can be fruitful:

- **Full adoption of methodology / framework,** VM is used to a high extent, the whole production is modelled including machines, cycle-times, failures, shifts, etc.. A good understanding of the AGV-system in its environment can be reached. If the AGV-system has novel functionalities that are not well-known these have been simulated at a single-vehicle perspective.

- **High adoption of methodology / framework,** the AGV-system is modelled to a very high level of detail, and a good understanding is reached about its performance. The environment is modelled to a less accuracy and the production system may not be validated, e. g. machines are not yet installed and planned cycle-times are used.
- **Low adoption of methodology / framework,** parts of the framework are used. Only parts of the AGV-system are modelled, or only a conceptual model of the AGV-system is made not including important details.

7. Evaluation of AGV Design Methodology

The third research case is designed to address the fourth objective by evaluating the unifying framework for the design process of AGV-systems. The objective of this research case is to evaluate the methodology with focus on industrial relevance, a complex environment to simulate, and the addition of functionality to the simulation model.

In the second research a pre-conceptual study for the automatic unloading of lorries was undertaken. The pre-conceptual study provided a base to continue the evaluation of the novel functionality, and the conceptual study resulted in acceptable performance of the SAV.

In this research case the performance of an AGV-system with the automatic unloading functionality will be evaluated. Complying to the methodology, the performance should be acceptable from firstly a single-vehicle perspective, and secondly and most importantly from a an AGV-system perspective. These aspects have been introduced step by step during the three scenarios of this research case. In the final scenario the detailed design will provide the best indication of the actual expected performance of an AGV-system design with multiple functionality SAVs.

An interesting note is that the AGVS configuration with the dual-load carriers with laser range-scanners shows a similar performance as the single load uni-directional configuration. But the first configuration also has time and capacity to unload the lorry, which is a considerable improvement.

7.1 Introduction

The proposed methodology has been applied and evaluated during this research study. A case study made by Bilge and Tanchoco (1997) was used as a basis for the manufacturing system to be studied. Mostly the same production data was used while the production layout was decreased in size.

An alternative to increase AGV fleet size to improve performance is to introduce vehicles with multiple load carrying capacities. Besides reducing congestion problems, the use of multi-load carrying AGVs can reduce the unproductive time of vehicles (Bilge and Tanchoco 1997). One commonly omitted aspect of AGV-system simulation is battery modelling, sometimes incorrectly believed to have minimal impact on system operation (McHaney 1995). The advantages of bi-directional guide-path systems over uni-directional have been discussed frequently in literature (Hoff and Sarker 1998).

These and other aspects will be studied in this research case with the principal aim to evaluate the proposed methodology of this thesis.

In the first scenario single-load AGVs operate on a uni-directional wire-path. In the second and third scenario SAVs operate on a bi-directional wire-path. The SAVs are models of the Euromation SAV.

7.1.1 Objectives of Study

The objective of this research case is to evaluate the proposed AGV-system design methodology.

This research case is intended to firstly evaluate the methodology by applying it to an AGV-system design problem, and secondly to focus on the objectives of the design problem. The design problem is an AGVS that is an integral part of a functional manufacturing system. In Table 8 the test scenarios of the study are presented. These test scenarios were designed to include most aspects of the AGVS-design methodology. Some aspects are however predefined, and are not evaluated, e. g. guide-path and production layout, and machine data.

Test Scenario	Description	Type of Guidepath	Shop loading
1	Decide AGV-fleet size for single-load AGVs	Uni and Bidirectional	30 loads / hour
2	Performance comparison of single and dual load AGVs	Bi-directional	30 loads / hour
3	Novel functionality development: Automatic unloading of lorry	Bi-directional	30 and 50 loads per hour

Table 8, Test scenarios of simulation methodology evaluation. The test scenarios present results from the study of several configurations.

There are three levels of adoption of methodology, as presented in section 6.6.3. This evaluation uses the methodology to a high extent, i. e. full adoption. The methodology was applied in the following four steps.

(i) **Conceptual design,** decide AGV-fleet size, type of guide-path (uni- and bi-directional)

(ii) **Detailed design,** single-load, dual-load vehicles, battery constraints, automated unloading of lorry.

(iii) **Application of novel function development,** laser range scanner for the automatic unloading of lorry.

(iv) **Find optimum production efficiency,** by simulation of a varying number of vehicles. An evaluation of the conceptually generated AGV-fleet size. Testing of the conceptually designed AGVS under many different circumstances e. g. different shop-loading.

7.1.2 Requirements of Research Case

There are several requirements of a research case to accommodate an evaluation of methodology. Since novelty in functionality of the AGV-system is an important aspect of the methodology this should be included. To cover a variety of manufacturing systems it is also of interest not study a similar system as the crankshaft manufacturing line presented in chapter 5. The following requirements have been identified for this research case:

- A functional workshop layout, to cover more than one type of manufacturing system (a line based production was the focus of study in chapter 5).
- Possibility to compare several aspects of novel AGV functions starting from a 'traditional' approach and then adding battery constraints, dual-load capacity, bi-directional guide-path, free-path capability, and automatic unloading of pallets from a lorry. These aspects are tested under both low and high production rates of the workshop.

Bilge and Tanchoco (1997) presented a research case to compare the performance of single and dual-load vehicles. Their work meets all of the above requirements and thus data from Bilge and Tanchoco's work provides the base for this research study.

The characteristics of the manufacturing system are:

i) A job-shop based layout.

ii) A potentially congested environment with a narrow guide-path layout with many potential blockings.

iii) High number of product variants, i. e. ten variants.

iv) Different routing for all products which increase complexity.

v) Realistic industrially related data.

vi) Possibility to increase effectiveness and efficiency by integrating additional functionality.

vii)

7.2 Description of the Manufacturing System

The test facility used in the simulation experiments is a job-shop with eleven departments. One machine in every department is the input station to the system, and one is the output station. There are nine machines in production. Each machine has one input and one output buffer, which are located next to the wire-path. The buffer capacity have been set depending on the required capacity between two and ten parts. No machine failures have been assumed to simplify the comparison between scenarios, which otherwise complicates the performance analysis.

There are ten products, or job types, that all have different routings between machines. No machines operate more than once on the same product, i. e. no products are routed back in the flow of material. There are no alternative routings where the same operation can be performed by several machines. The process plan and job mix for the test problem is:

Job Type	Route	Job Mix
1	1,2,3,6,7,10,11	0.20
2	1,4,5,8,9,11	0.10
3	1,3,4,10,11	0.12
4	1,2,5,6,7,8,11	0.10
5	1,3,4,10,11	0.08
6	1,2,3,5,8,9,11	0.04
7	1,3,4,6,10,11	0.12
8	1,2,5,9,11	0.06
9	1,4,9,10,11	0.12
10	1,2,3,5,11	0.06

Table 9, Process plan and frequency of jobs. Each job type relates to a product variant. The lot size of a job is three products. The job mix represents the relative frequency of the job.

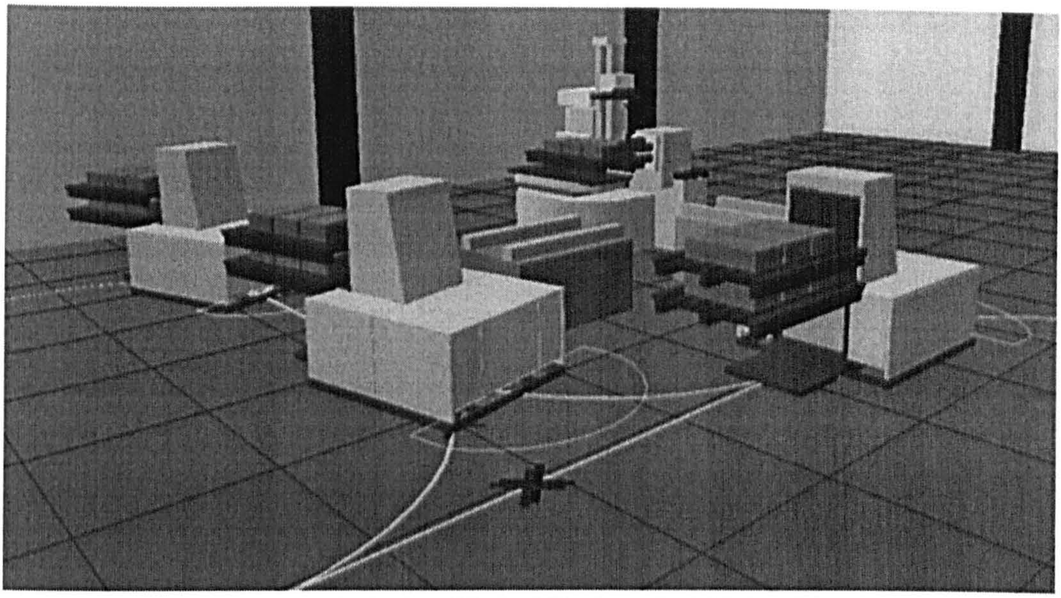

Figure 50, A three way crossing in the guidepath layout. The figure shows a crossing where several routes are possible for the SAV, since the guidepath is bi-directional. Decision points (the crosses on the guidepath) in combination with tokens are used to avoid front-to-front dead-locks.

The simulation model was developed in Quest DES-simulation software. Quest provides both an interactive simulation interface, and an application language for the programming of non-default objects. Many of the default objects have been used, e. g. machines, buffers, but application programs were also developed for the AGV-system functionality.

When an AGV loads or delivers material it stops on the wire-path, waits for an assumed load / unload time (in this case 30 seconds) while blocking the path, and then continues. The AGV-speed is 1.0 metres/second on straight path segments, and 0.6 metres/second on curved segments. Acceleration and deceleration is 1 m/s*s. In the first scenario single-load AGVs operate on a uni-directional wire-path. In the second and third scenario SAVs operate on a bi-directional wire-path. The SAVs are models of the Euromation SAV presented in section 2.3.4, and sections 6.1 to 6.5.

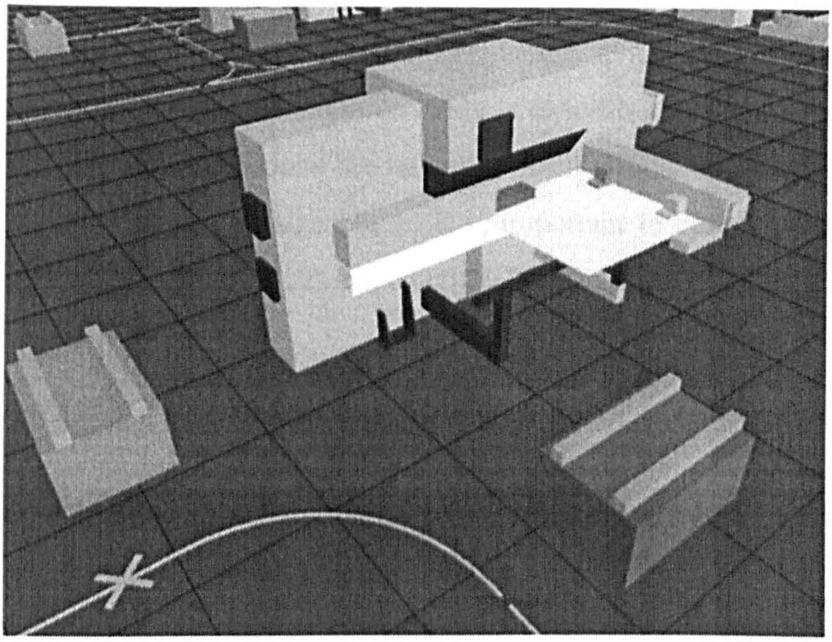

Figure 51, One of the machines in the simulation model. The buffer to the front right of the machine is the AGV unload point and the buffer to the left is the load point. The load transfer is made via the decision point in front.

Modifications to the data from Bilge and Tanchoco's work are:

- The layout size and proportions.
- Exact location of input and output buffers and machines.
- The production scenario is in this research case assumed to be production of injection moulding forms.
- Lot sizes for all products are three. Products are transported on pallets three by three.
- The machines are given geometrical representations to illustrate the power of visualisation which is an integral part of the VM concept, e. g. the VSOP-model, presented in chapter 3. The machine CAD-geometries represent milling machines, welding machines etc. as a part of the production scenario.

7.2.1 Assumptions in the Model

The challenge of a simulation study is to reach a sufficient level of detail of the model which still can produce the requested results. This is the same for both the conceptual and the detailed design phase. It is important to clearly state these limitations of the model so that the results can be critically examined in the light of the made assumptions.

The following assumptions were made concerning the model in this research study:

- No machine failures are used.
- Lot-sizes are three for all ten products.
- Default Quest AGV control logic is used.
- AGV recharging time is considered in the last scenario.
- AGV failures are not considered. Occasionally real AGVs fail e. g. lose their guidepath and causing congestions. This was estimated to have little effect on system performance provided that operators were fast to detect and address the problem.
- AGV parking and idle-vehicle procedures are modelled.

7.3 AGV-system Simulation in Quest

The AGV-paths are represented by segments either a straight line or curved section. AGV segments form the AGV path system on which AGVs can travel.

The AGV controller is used to control globally one or many AGV classes with respect to a set of AGV decision points. A controller can provide instructions to AGVs concerning which path to take and can select which AGV to use for a given task. An AGV is an MHS element. It represents a predefined material-handling construct that can transport multiple parts from one AGV decision point to another.

There are three levels of control of AGVs in Quest. These are in order of priority:

- Decision points, local controllers that can be used to load and unload material to AGVS, for zone-control, and traffic management.
- On-board local AGV-controllers, motion considerations are made.
- Central AGV-controller, handles scheduling and vehicle dispatching.

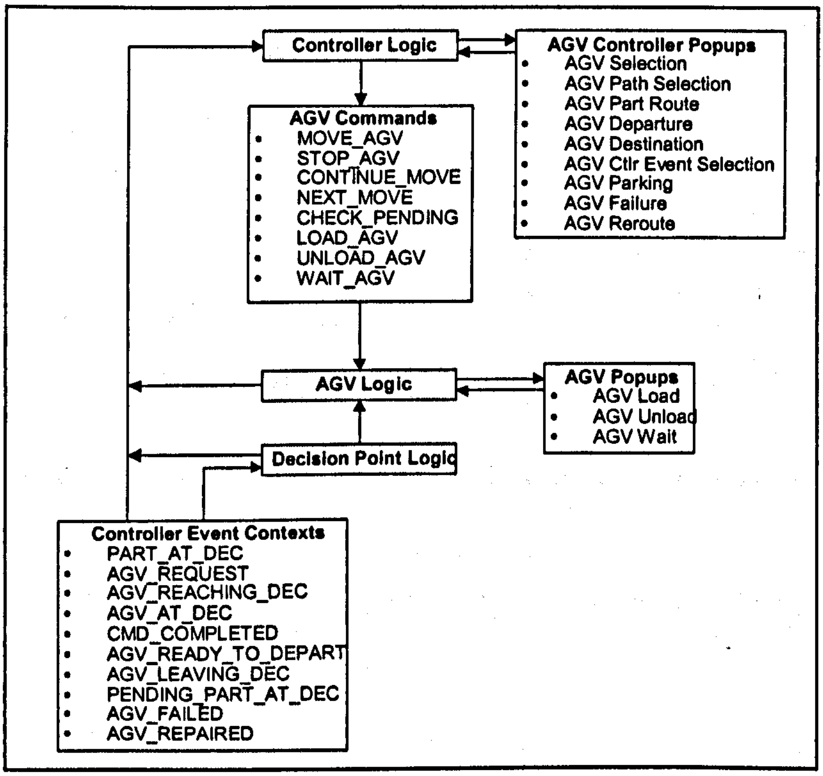

Figure 52, Structure of AGV-commands in Quest. There are three possible levels of control when simulating AGV-systems in Quest. These are with increasing priority: i) the central controller, ii) on-board AGV-control, iii) and decision point control. Decision points are 'local controllers' which can be used e. g. at intersections. Decision points over-ride the other levels in case of conflict e. g. the central and the AGV controller issues a move-command and the decision point issues a stop-command, the AGV stops.

The three levels of control communicate by sending messages and commands. Each central controller, AGV, and decision-point has a process-logic attached. Figure 52 shows the control structure and flow of information in a Quest-model. If an AGV or a decision-point receive contradictory commands, the priority order is used.

All the experiments in this research case include a warmup time before statistics were collected. The simulated time was 40 hours in each scenario, and eight of these were warm-up time. During that time the machines and buffers have been loaded and all jobs have been released for production several times (the lowest relative job mix of 0.04 gives 30 jobs/hour * 8 hours * 0.04 = 9.6 released jobs of that type). The figures presenting the results all show the output of 32 hours production.

7.3.1 Material Flow Through the Simulation Model

To define the material flow through the logical system connections have to be made and also logical selections included where appropriate. The flow starts at a source element which enter pallets according to the shop-loading and the relative setting of job-mix, see Table 9. Connections are then required to and from each element that handles the pallets e. g. AGV-decision-points, buffers, and machines though not each individual AGV. Finally the flow is terminated at a sink where statistical data is collected.

The production control of the real system is of push type. The frequency of arrival of material to the first station controls the shop-loading. Two settings were investigated: 30 jobs per hour, and 50 jobs per hour.

7.4 First Scenario: Decide AGV-fleet size for single-load AGVs

AGV-fleet size estimation has received much attention in research and many methods have been proposed. A simulation method used by Bilge and Tanchoco is in many aspects superior to most other methods. It is applied in the detailed simulation phase of AGV-system design. Several fleet-sizes are tested for key performance measures and evaluated. It can be useful to test several scenarios including worst-case scenarios. The fleet-size will be the result of detailed considerations of the AGV-system and its environment, e. g. production data, failures and other disturbances, battery-considerations, idle-vehicle location, and dynamic phenomenons in the material flow.

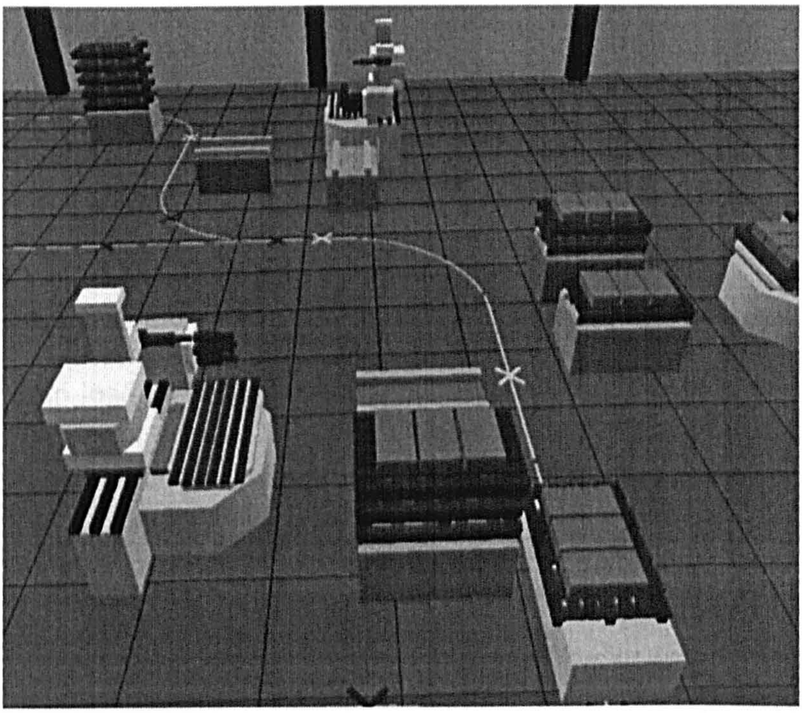

Figure 53, A single load AGV. Some of the non-bottleneck machines are also shown; their output buffers are almost full.

The warmup time in this case study is eight hours i. e. when no statistics were collected. The total simulated time was 40 hours. During that time the machines and buffers have been loaded and all jobs have been released for production several times (the lowest relative job mix of 0.04 gives 30 jobs/hour * 8 hours * 0.04 = 9.6 released jobs of that type). Figure 55 shows the output of 32 hours production.

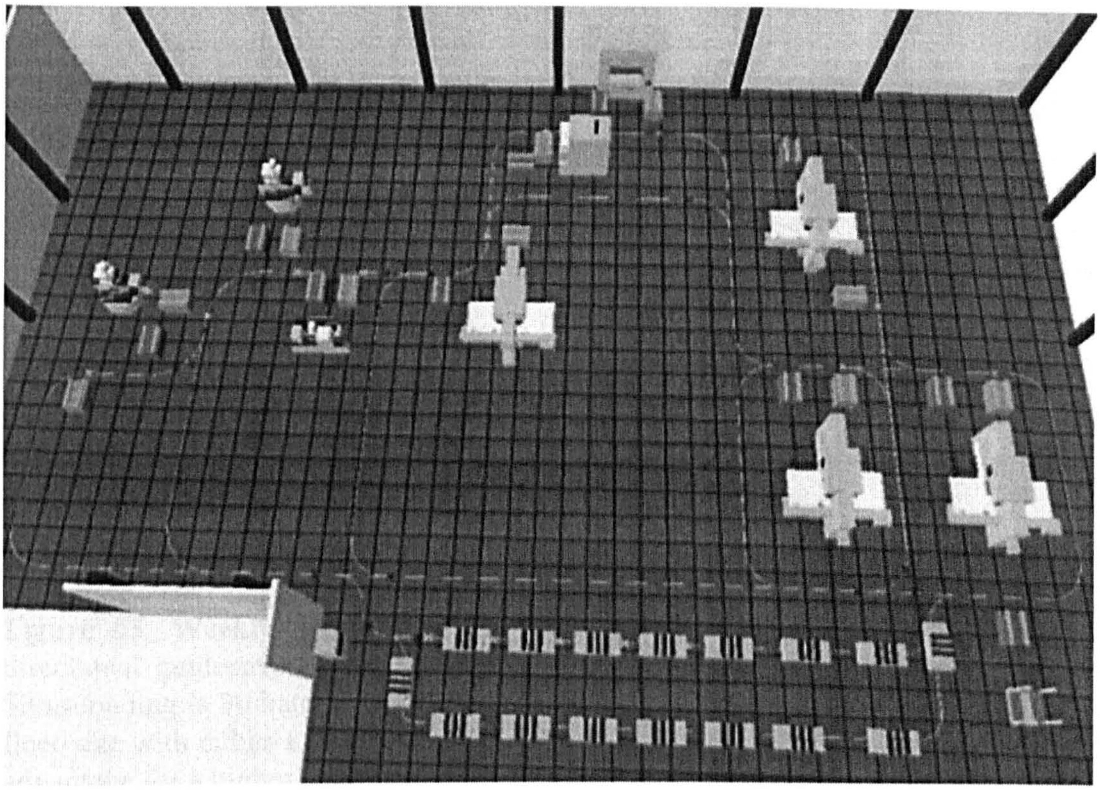

Figure 54, Largest AGV-fleet configuration. To test how the AGVS performs with an extensive fleet size, 16 AGVs where included. The results show that above a certain fleet-size the production output is approximately the same, and then decreases for increased number of vehicles, due to congestion. The guidepath is unidirectional and the shop-loading is 50 jobs per hour.

A maximum production output is reached at seven AGVs, and the introduction of more vehicles does not improve the production performance, but does not decrease it either. In Figure 54 an AGV-fleet of 16 AGVs is shown as an approach to see if congestion of considerably many vehicles reduces the output. As Figure 55 shows this was not the case, an almost constant output just above 800 finished batches is reached. The congestions however become obvious during simulation since the simulation runs frequently went into a state of dead-lock. The generous parking location also diminishes the disadvantage of too many vehicles.

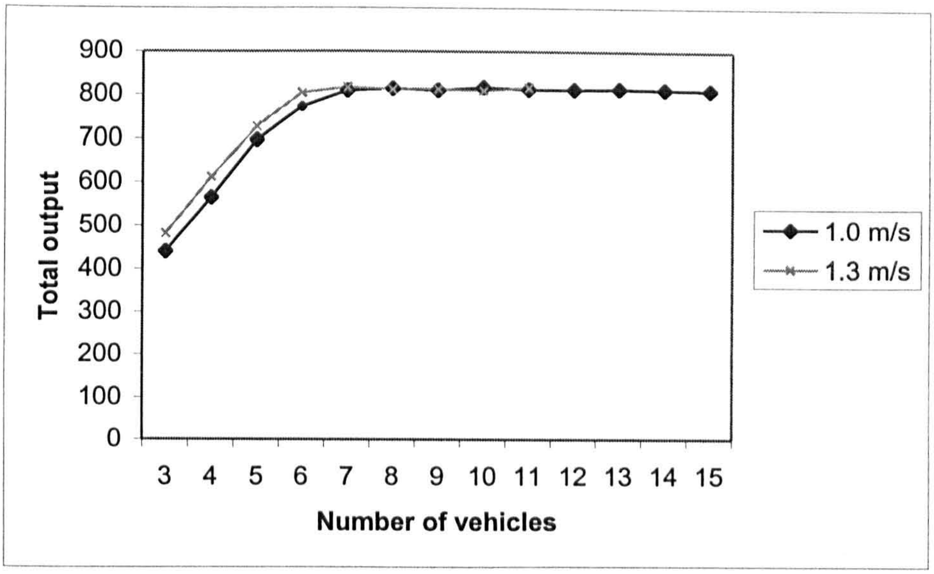

Figure 55, Weekly production for AGV-system with varying speed. For a bi-directional guidepath layout with single-loading vehicles and no recharging assumed. Shop-loading is 30 batches per hour. The diagram shows the output for a varying AGV fleet-size with either 1.0 or 1.3 m/s as the maximum guide-path speed. There is a small advantage for a higher speed layout up to seven vehicles where apparently the maximum production rate is reached for this configuration.

An increase in maximum speed for certain long sections of the guide-path layout was tested. The result was little or no influence on the production output, as shown in Figure 55. The layout is too small for higher speeds to improve the performance significantly. The unidirectional guidepath configuration has been included for comparison with the bi-directional layout. For this research case the difference was however minimal since very few 'short-cuts' were possible which would have been advantageous for the bi-directional layout. If recharging batteries is included during production time, productivity decreases however.

7.5 Second Scenario: Performance comparison of single and dual load vehicles

An alternative to increase AGV fleet size to improve performance is to introduce vehicles with multiple load carrying capacities. Besides reducing congestion problems, the use of multi-load carrying AGVs can reduce the unproductive time of vehicles (Bilge and Tanchoco 1997).The effectiveness of single-load and dual-load AGVs are compared using simulation.

In this scenario a bi-directional guidepath layout with a shop-loading of 30 loads per hour has been used to compare the performance of single and dual-load vehicles.

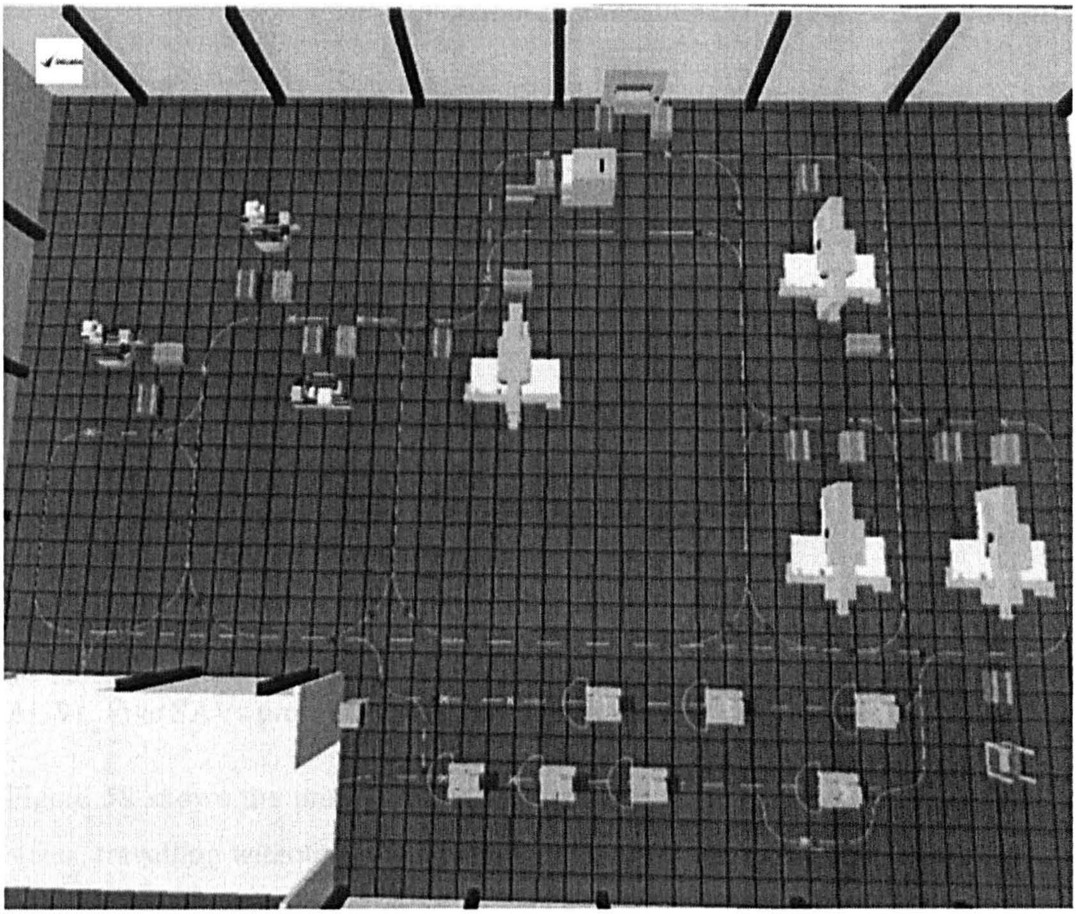

Figure 56, The job-shop production layout. In this AGVS configuration there are seven dual-load SAVs in start position. They are located at the parking segments at the lower part of the figure. One battery recharging station is located at the lowest by-pass of the guide-path layout.

Figure 56 shows the whole production layout. There are 9 production machines, each with unique operations. The AGV-fleet in Figure 56 is seven SAVs with dual load functionality which operate on bi-directional guide-paths.

The warmup time of this case is eight hours, i. e. when no statistics were collected. The total simulated time was 40 hours. During that time the machines and buffers have been loaded and all jobs have been released for production several times. Figure 57 shows the output of 32 hours production. The difference between the two AGVS-configurations is considerable, for an AGV-fleet of 3 the SAVs produce 25 parts more, for fleet-sizes of 4 and 5 SAVs produce 48 parts more, and for a fleet-size of six vehicles the SAV-configuration produces 29 parts more.

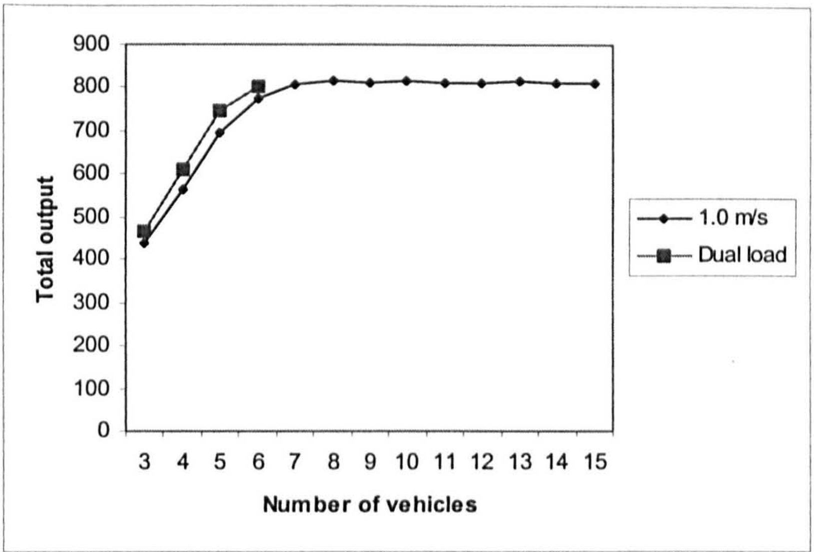

Figure 57, Comparison of single-loading and dual loading AGVs. Shop-loading is 30 batches per hour. The diagram shows the difference between single and dual load AGVs. Five SAVs produce nearly as many parts as six single-load AGVs.

Figure 58 shows the proportion of the time that the AGVs on average spend in three states, travelling without load, travelling with load, and in idle state – parked. For more than six vehicles, the time spent in idle-parked increases and the loaded travel time decreases. The same jobs are shared between more vehicles. These observations indicate the same as figure 55 in section 7.4 that fleet-sizes above 6 to 7 vehicles does not add to productivity.

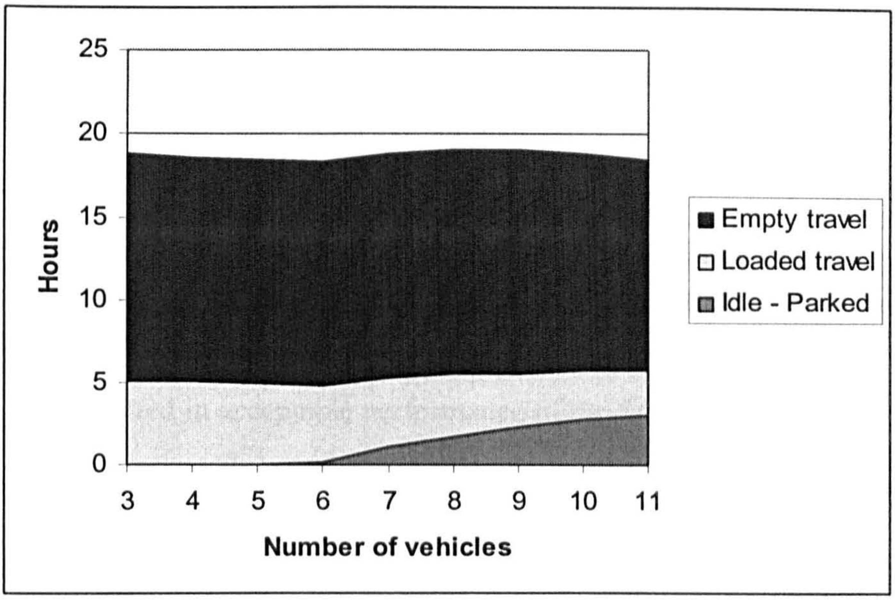

Figure 58, Average time in different states for a vehicle. For a bi-directional guidepath layout with single-loading vehicles and no recharging assumed. Shop-loading is 30 batches per hour. The diagram shows time spent in either empty travel, loaded travel, or idle state. For a vehicle-fleet of more than six vehicles much time is spent in idle state. A larger fleet size reduces time spent for loaded travel but not empty travel.

7.6 Third Scenario: Development of Novel Functionality

The methodology for evaluating novel functionality is tested. In the second research case a pre-conceptual study for the automatic unloading of lorries was undertaken. A conceptual study from a vehicle-perspective was made on the technologies enabling the automatic unloading: i) sensor simulation of the laser range scanner, and ii) emulation of the Carrier Control System of the Euromation SAV. The pre-conceptual study provided a base to continue the evaluation of the novel functionality, and the conceptual study resulted in acceptable performance of the SAV.

According to the methodology, the performance should be acceptable from both the single-vehicle and the AGV-system perspective.

The detailed considerations have step by step been introduced during the three scenarios of this research case. In this final scenario the detailed design will provide the best indication of the actual expected performance of an AGV-system design with multiple functionality SAVs.

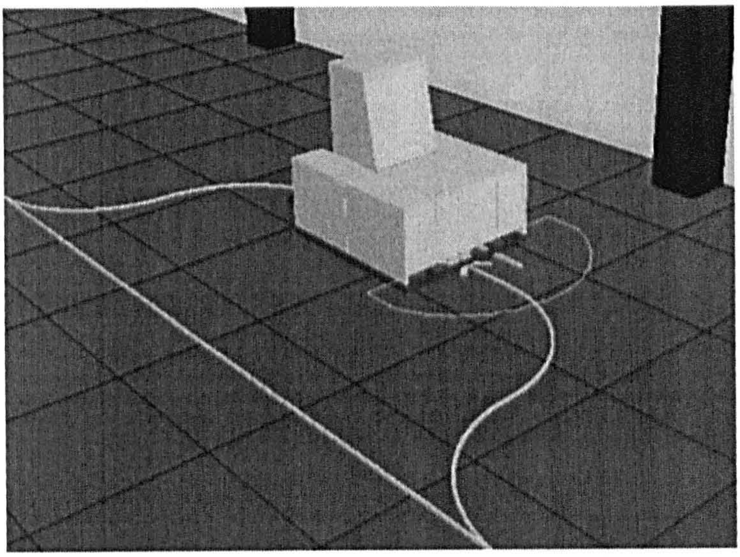

Figure 59, An SAV at the recharging point. The recharging process occurs during production. As a result approximately one vehicle less of the SAV-fleet is available, depending on the total number of vehicles.

The guidepath configuration is bi-directional and the shop-loading is in the first case 30 loads and in the second case 50 loads per hour.

In this scenario the battery recharging process is included. Every vehicle must after a certain time in production go to the recharging point, shown in Figure 59, and recharge its batteries. A comparison is shown in Figure 61 of the difference in production output including the recharge process. For an AGV fleet-size of 3 vehicles the difference is 52, for a fleet-size of 4 it is 68, for five vehicles: 81, and for 6 vehicles it is 42 parts. The difference is significant in all cases and the difference decreases only for sufficiently many vehicles.

The novel functionality of automatic unloading of the lorry is shown in figure 60. The SAV has left the guide-path and is navigating freely to enter the lorry.

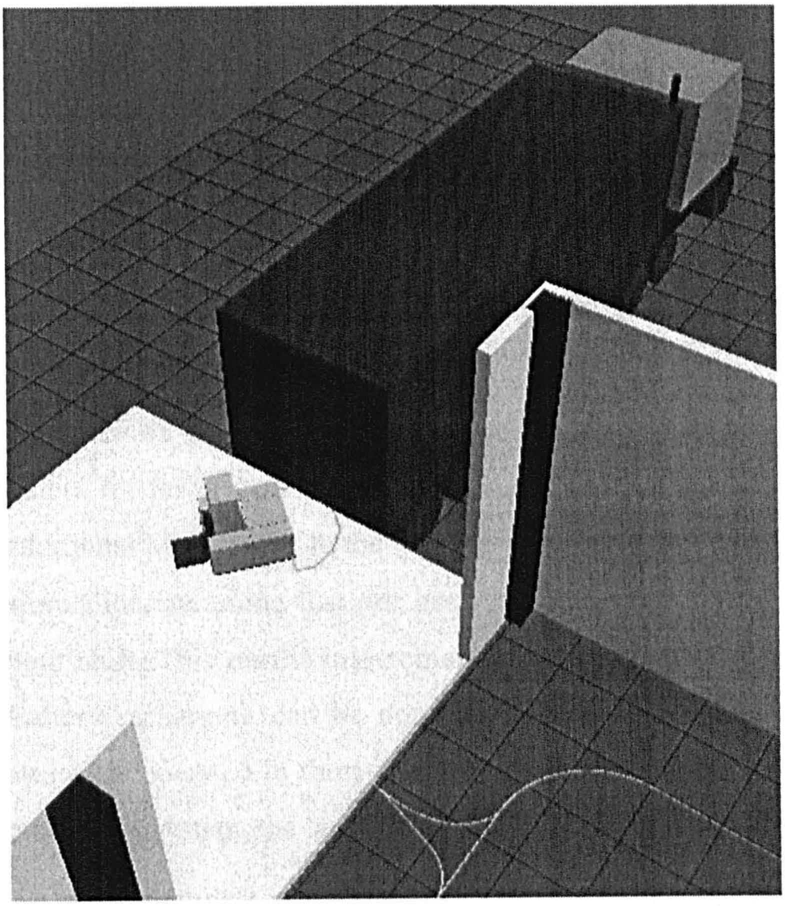

Figure 60, A SAV is commencing unloading a lorry. The SAV has left the guidepath and is preparing to unload the lorry.

The estimated time of unloading is assumed to be higher than for normal loading within the plant. The flow out from the production system is assumed to be to another division of the plant, so the loading of lorries is not included.

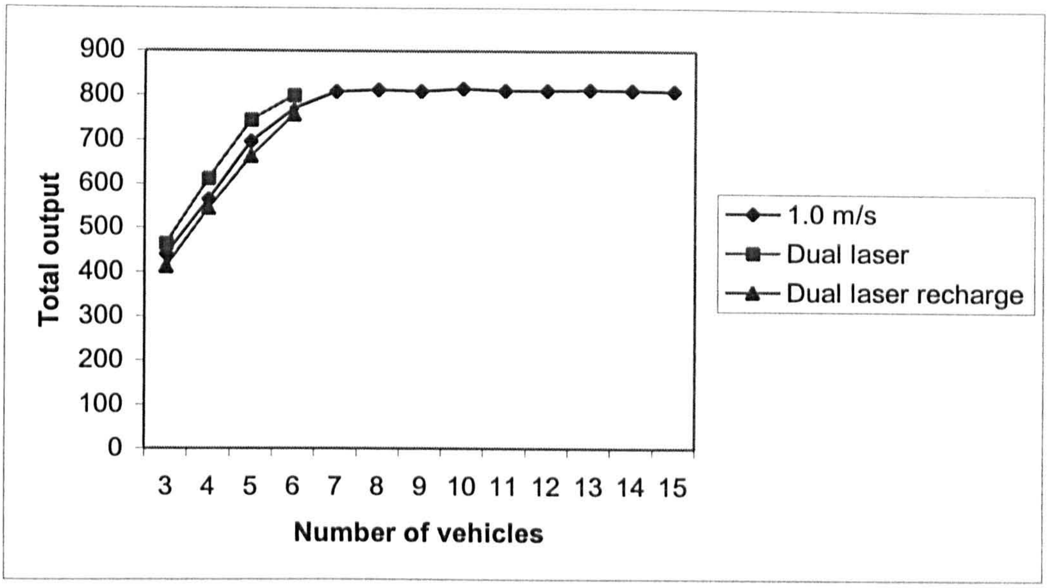

Figure 61, Production output for three different configurations. The diagram shows the output for three different AGVS configurations. 1.0 m/s is a configuration with single-loading vehicles showed for reference. 'Dual laser' is a configuration with dual-load vehicles, which also picks up parts in the delivering lorry. 'Dual laser recharge' also includes the recharging of vehicles during production. A bi-directional guidepath layout with a shop loading of 30 batches per hour is assumed.

In Figure 61 the dual load configured vehicles (indicated dual laser) provide a higher output for fewer vehicles than the single load configuration, and still they carry out an additional MHS tasks. In the third case the battery recharging process is included in the simulation, assuming that one hour recharging is required for each vehicle every eight hour shift. This results in a somewhat lower output but the scenario is more realistic. Battery recharging can be done during non-production hours, but if the production system is operated in three-shifts 24 hours a day, which is not unlikely for a high cost automated system, the last scenario is the more realistic one.

An interesting note is that the AGVS configuration with the dual-load carriers with laser range-scanner shows a similar performance as the single load uni-directional configuration. But the first configuration also has time and capacity to unload the lorry, which is a considerable improvement.

Bilge and Tanchoco (1997) discussed the same phenomenon though their results showed a larger difference in performance between single load and dual load vehicles. This can be explained by the layout size, and that the SAVs in this simulation require more space and thus cause more congestion.

7.7 Discussion and Conclusions

The objective of this research case was to evaluate the methodology with focus on industrial relevance, complex environment to simulate, and the addition of functionality to the simulation model. The simulation methodology proved successful in supporting the development of a detailed development phase, the introduction and evaluation of novel functionality, for a complex environment. Conclusions of the detailed methods that can be based on this research case are:

The method for deciding AGV-fleet size used by Bilge and Tanchoco was found to be in many aspects superior to most other methods. It is simulation based and applied in the detailed simulation phase of AGV-system design.

When detailed aspects of importance have been included in the simulation model several fleet-sizes are tested for key performance measures. It can be useful to test several scenarios, also including worst-case scenarios. These are important if some of the data is estimated or in other ways inaccurate.

The fleet-size will be the result of detailed considerations of the AGV-system and its environment, e. g. production data, failures and other disturbances, battery-considerations, idle-vehicle location, and dynamic phenomenons in the material flow. No other reported methods reach the same accuracy. The main disadvantages of this method are that it is:

i) **Time consuming,** the time to carry out a simulation study can add too much time to an AGVS design project, if not made concurrently.

ii) **Potentially costly,** in terms of software and time. This is however a balance between cost and benefit in terms of accurate design.

iii) **Too cumbersome,** for small AGV-systems where a simulation study is not necessary for deciding other aspects.

If simulation is used for strategic or other reasons, the detailed simulation approach shows considerable advantages to produce accurate AGV-system designs.

8. Conclusions

A methodology has been proposed for the use of simulation in AGV-system design which is divided into: firstly development of traditional AGV Systems, and secondly development of novel AGV Systems, e. g. SAV-systems. The traditional system development option will not require use of GES, as the functionality of it is well known. So the use of a DES should be sufficient for this task. The novel system development includes the use of both GES and DES, firstly to develop, conceptually test the novel functionality, and secondly to make a detailed design of the systems, and test and evaluate it, potential problems of the novel AGV-system when operating in its intended environment.

8.1 Research Findings

Two main perspectives have been identified of AGV-system development, the single vehicle perspective, and the AGV-system perspective. Both play an important role for the development of novel AGV-systems. Traditionally AGV-simulation has been almost equivalent with discrete event simulation from a system perspective, as the research review indicates (see appendix 1).

The conclusions for AGV-development that were made from the first research study are:

- To include a detailed simulation phase in a AGVS-development process should be valuable if:

  i) the production system is large, (approximately more than five machines and five AGVs).

  ii) performance of the production system is difficult to predict due to failures, break-downs, untested technology, or the scheduling of limited resources.

  iii) it is important to involve many people in the development process.

iv) there is little time for development and the process must not be delayed.

- A simulation study of this size strongly motivates the use of a structured simulation methodology to produce an acceptable model.
- Thorough validation is required

In the second research case a framework of an SAV with the Carrier Control System, script commands, and a virtual environment were developed. With this framework AGV functionality can be developed in a structured and realistic way. Conclusions from the second research case are:

- The operational characteristics of navigation algorithms can be investigated and used within their limits, e. g. how robust a wall-following algorithm is to objects that clutter the wall.
- Navigation techniques that are not robust enough to be the main navigation technique can be used as a complement.
- Concurrent navigation techniques can be developed.
- Material handling equipment can be evaluated in aspects of reachability, collision hazards with other objects when the mechanical devices are in certain positions, etc..
- AGV-system applications for non-existing environments can be developed.

The third research case focused on the evaluation of the proposed simulation methodology for novel AGVS design. This was achieved by analysing and testing several configurations of an AGV-system using the simulation methodology. The methodology includes a detailed simulation phase, and a novel methodology development part. The detailed simulation is stressed as being of high importance for a short and successful design process of novel AGV-systems. Some focus was directed to this detailed phase in the research study. The most advanced configuration included: i) bi-directional guide-path layout, ii) battery recharging facility, and iii) vehicles with a dual-load capacity load handler and an LRS based navigation system. The navigation system was used to traverse off the wire guide-path onto a docking bay and without human involvement unload lorries with incoming material.

The conclusions from the study were:

- A unidirectional guidepath configuration was tested and compared with the bi-directional layout. For this research case the difference was minimal since very few 'short-cuts' were possible which would have been advantageous for the bi-directional layout.
- If recharging batteries is included during production time, productivity decreases. Recharging batteries during production would be necessary for 24 hours a day production in three shifts.
- The AGVS configuration with the dual-load carriers with laser range-scanner shows a similar performance as the best single load configuration where 1.3 m/s maximum speedis allowed. But the first configuration also has time and capacity to unload the lorry, which is a considerable improvement.

The conclusion for the detailed design methodology was that it provides a great advantage for novel AGV-system development.

8.2 Main Contributions to Knowledge

In this thesis a unifying simulation framework is proposed for the structured development of AGV-systems with novel functionality. The framework includes a methodology, novel functionality development, and a developed virtual environment for the simulation of semi-autonomous vehicles. The simulation approach is based on two 3D graphical simulation tools, one discrete-event based (DES), and one geometry simulation tool (GES). This combined approach brings significant benefits to the design process of the AGV-systems of the future.

One of the anticipated advantages are reduced development project life cycles and shorter time-to-market for end users of AGV-systems. These will strongly benefit from shortening delivery lead-times, but also reducing risks and costs of AGVS-development projects. The adoption of industrial standards, e. g. STEP and the use of a component based development of novel AGV-systems enhances portability, scalability, and future problem analysis of the produced system. Realisation is also improved via a high degree of reconfigurability and scalability since the same application can be reconfigured for different customers with minimal reengineering. After installation the simulation model becomes a powerful tool for troubleshooting and for the analysis of worst-case scenarios, or for the day-to-day operative planning and scheduling. The framework brings significant benefits to AGV-system builders and users. To the authors knowledge this is the first time that a combined approach of single-vehicle level together with an AGV-system level and the combined use of DES and GES in a VM context, has been proposed for the development of novel AGV-systems.

This research study has advanced development by offering a framework for developing testing and evaluating AGV-systems, based on concurrent development using a virtual environment. The ability to exploit unique or novel features of AGVs based on a virtual environment improves the potential of AGV-systems considerably.

8.3 Future Work

Future research in AGV-system design can be beneficial in two main directions, firstly research in simulation and optimisation related areas, and secondly in more industrially related research, i. e. filling the gap between theoretical contributions and industrial implementations.

The integration aspects of simulation tools provide interesting research topics. There is a need to improve the integration possibilities between simulation tools, and between simulation tools and shop-floor control systems regarding AGVs and AGV-system controllers. The proposed framework for developing, testing, and evaluating AGV-systems would strongly benefit from a better integration which would improve the validity of a model where an AGV-system model use the same controller as the real system.

Much work is carried out twice when modelling AGVs in both DES and GES tools. A better integration between the tools and better AGV-modelling capabilities can shorten the simulation model development time significantly. E. g. of integration issues are AGV-geometry and operational information, and environment geometry information.

Another interesting research question is a combined AGV-system modelling approach for DES-tools and optimisation techniques. The optimum design solution is not provided by means of simulation but rather from optimisation techniques. A combined modelling capability of a tool providing input for both optimisation approaches and discrete-event-simulation should generate a near optimum and evaluated solution faster than today.

List of Figures

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List of Acronyms and Abbreviations

3D	3 Dimensional
AGV	Automated Guided Vehicle
AGVS	Automated Guided Vehicle System
AMHS	Automated Materials Handling System
ANN	Artificial Neural Networks
CAR	Computer Aided Robotics
CNC	Computer Numerical Control
CCS	Carrier Control System
DES	Discrete Event Simulation
DMU	DeMontfort University
EC	European Commission
FL	Fuzzy Logic
FMS	Flexible Manufacturing System
GES	Geometry Simulation
HMI	Human Machine Interface
IEE	Institution of Electrical Engineers
IEEE	Institution of Electrical and Electronics Engineers
JIT	Just-In-Time
LRS	Laser Range Scanner
MDT	Mean Down Time
MHS	Materials Handling System

MIT	Massachusetts Institute of Technology
MR	Mobile Robot
MTBD	Mean Time Between Down
MTTR	Mean Time To Repair
NIO	Not In Order
OLP	Off-line Programming
PID	Proportional Integrated Derivative
PLC	Programmable Logical Controller
SAV	Semi-autonomous Vehicle
SME	Small and Medium sized Enterprise
VGI	Vehicle Ground Interaction
VM	Virtual Manufacturing
WIP	Work In Progress

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Appendix 1: Research Review Summary

Author	**Software**	**Vehicle Path Design**				**Assumptions**				**Simulations**	**Objective**
		idle veh. loc.	no veh.	dispatch	flow direct	block	varying no veh.	battery	acc/dec other	Theory model or real system testing	Nav, (schedule) guide-path, sim-improve
Evers and Koppers 1996	?	-	-	x	both	x	x	x	x	both	c-sys traffic -control
Mellado et. al. 1999	-			x	?	x	x	x	x	no sim, real sys Th. made intro SAV in real	nav. Free-nav + wire
Ho, Ying-Chin 2000	?	-	x		-	x	?	-	-	Theo. Dynamic zone strategy	collision traffic controls prevent
Oboth et.al. 1999		x	x	x	bi	x	-(?)	-	varying speed	Traffic-control conflict free route theoretical	aut.nav 3D Laser based Nav + operation
McHaney 1995		na	na	na	na	na	na	x	x	Theoretical Battery-modeling	sim-improve
Lee, Jim et.al. 1994	SIMAN	-	na	x	uni	x	-	-	-	arrival distr. Affect layout	Evaluate trad. + tandem layout
Malmborg 1992		-	x	x	bi	x	-	-	-	Theory Analytical + sim approach to zone control	Handle all major dec. var. Design zone ctrl AGVS
Narasimhan et. al. 1999		-	-	x	bi	x	x	x	inter-ruptions	Theory sim.	Sim improve, add vehicle interruptions
Gaskins et. al. 1989		-	-	-	uni bi	-	-	-	-	Theory, no sim	Virtual flow-path design
Taghaboni-Dutta 1997	AGVSim2	-	-	x	both	x	x	-	-	Theory, sim	Dispatching VALVE-algorithm
Bilge, Tanchoco 1997	AGVSim2	-	x	x	-	x	x	-	-	Theory, sim	Multiplex-load carriers

Author		Software	Vehicle Path Design				Assumptions				Simulations	Objective
			idle veh. loc.	no. of veh.	dispatch	flow direct	block	varying no veh.	battery	acc/dec other	Theory model or real system testing	Nav, (schedule) guide-path, sim-improve
Lee, Jim et. al.	1990	SIMAN	-	-	-	uni	x	x	-	-	Only simulation	Evaluate AGVS design using simulation
Arkin and Murphy	1990		-	-	-	-	-	-	-	-	Navigation in manuf. env. non guide-path	Dev. Nav. Method without significant restructuring of workplace
Balogun and Popplewell	1990		A cronological comparison on no of papers of different solution approach								Review of AI NN, GA, FL, heuristics and more. Objectives in scheduling	Integration of FMS scheduling. A context to solution methods used, also in AGVS design
Bookbinder and Kirk	1997	SIMAN	-	-	x	uni	x	-	-	-	Theory + simulation. Use of assy carrier.	Lane selection rules in parallel assy line (unbalanced). Assumtions: straight lines sufficient not vehicles.
Shen and Kobza	1998		-	x	x	uni	-	x	-	Fixed travel lines	Theory + analysis queuing theory + Markov processes, tested using simulation	Find minimum no of vehicles related to dispatching rules with small risk of local waiting,
Arifin and Egbelu	2000	AGVSim	-	x	-	both	-	x	-	-	Theory analytical sim. Facility char´s stat. significance on contribution to veh. req.	No of vehicles using statistical regression analysis.

Author	Software	Vehicle Path Design				Assumptions				Simulations	Objective
		idle veh. loc.	no. of veh.	dispatch	flow direct	block	varying no. veh.	battery	acc/dec other	Theory model or real system testing	Nav, (schedule) guide-path, sim-improve
Lee and DiCesare 1994		-	-	x	both	x	-	-	job devoted one AGV	Theory, analytical + sim., petri-nets and heuristic-search	Integrated scheduling of part processing & AGV-system, centralised & disrtibuted
Ülgen and Kedia 1990	SLAM SYSTEM	-	-	x	uni	x	x	-	x	Theory taxonomy of AGV design, real case study+ sim	Provide comprehensive summary. The effects of transit paths in AGVS design
Liu and Hung 2001	Automod		-		bi		-		a voiding dead-lock no acc/dec	Theory + sim propose control strategy	Control strat for single vehicle multiload, global real time shop info
Kim et. al. 1997	MAPS	-	-	x	bi	x	-	-	deadlock	Theory + sim	Dead lock prevention
Lee, J. et. al. 1996	SIMAN	-	-	x	uni	x	x	-	varying speed	Theory, sim 2400 runs	Single multiload vehicle. Load selection. Multiload vehicle
Srinivasan et. al. 1994		-	-	x	both	-	-	-	-	Theory, analytical model+sim	Pre-simulation
Lee, Jung Hong et.al. 1998		-	-	x	both	x	-	-	x	Theory, sim	Collision free min-time motion
Shah et. al. 1997		-	-	x	bi	x	-	-	-	Theory+ sim	Conflict-free shortest path, scheduling production-order driven

Author	Software	Vehicle Path Design				Assumptions				Simulations	Objective
		idle veh. loc.	no. of veh.	dispatch	flow direct	block	varying no veh.	battery	acc/dec other	Theory model or real system testing	Nav, (schedule) guide-path, sim-improve
King and Kim 1995	AGVTalk	x	x	x	both	x	x	x	x	Simulation env. Object oriented much like Quest	Simulation tool compared with general purpose sim languages
Mantel and Landeweerd 1995		-	x	x	both	x	x	-		Real system study. Taxonomy of transport control + sim	Path layout transport control integrated transport + prod. control
Rajotia et. al. 1998		-	-	x	both	x	x	-		Theory + sim	Config. Of mixed bi/uni flow path
Seifert et. al. 1998	SLAM2	-	-	x	?	x	x	-	dynamic obtacles	Theory + sim. Feedback control system, blocking pedestrians	Sim as short-term decision tool for AGV routing, vehicle routing strategies, global vision
Shan, et. al. 1997		-	-	x	bi	x	x	-	-	Theory + sim, product structure MRP modules	Integrated AGVS control model with production control. Lit.review, conflict-free routing, static structure + state transition diagrams
Rajotia et. al. (2) 1998		-	x	x	uni	x	x	-	-	Theory + sim + analysis	No of AGVs for certain mhs-task
Nakano and Ohno 2000	ROPS2	-	x	-	uni	-	x	-		Theory + sim + analysis, buffersize, w/s location no of AGVs	Integrated analytical/sim approach for design of AGVs in JIT env.

Author	Software	Vehicle Path Design				Assumptions				Simulations	Objective
		idle veh. loc.	no. of. veh.	dispatch	flow direct	block	varying no. veh.	battery	acc/dec other	Theory model or real system testing	Nav, (schedule) guide-path, sim-improve
Kim and Tanchoco 1990	AGVSim2	-	x	x	both	x	x			Sim + real vehicle control architectures	Free-path vehicles design of ctrl arch. Integration requirements
Sun & Tchernev 1996		-	-	-	uni	-	x	-	-	Theory, analytical branch & bound search large systems	Optimal flow path for unidirectional AGVs. Review on flow-path design
Shen and Lau 1997		-	x	x	uni	-	x	-	-	Theory, analytical integer programming + heuristic rule based on service time to improve	Flow path design so expected wait time-design is minimized
Narasimham et. al. 1993		-	x	x	bi	x	x	-	-	Theory, analytical column generation procedure + sim	Static routing with known demand assignment, bidirectional path, conflict-free routing
Hoff and Sarker 1998		x	x	x	both	x	x	-	x	Theory, summary on analytical, sim etc.	Literature review design of guide paths and dispatching rules. Survey on guide path design
Maxwell and Muckstadt 1982		-	x	x	uni	x	x	-	-	Theory, analytical +sim, assumes constant prod. rate	Design of AGV-systems
King and Wilson 1991		x	x	x	both	x	x	-	x	Theory, summary on analytical, sim etc.	Literature review design of guide paths and dispatching rules. Survey on guide path design

Author		Software	Methodology	Analytical approach	Objective Nav, (schedule) guide-path, sim-improve
Williams and Orlando	1998	Witness + IGRIP	Banks and Gibson	Ergonomic analysis des, statistic analysis	Find optimum design for final engine assy work station
Klingstam and Olsson	2000	Quest	Own method	DES, statistical analysis, structural workproc.	Use of DES for continous process verification in industrial system development
Law	2001		Law & Kelton	DES, structured methodology	How to develop valid and credible sim. Models
Park et. al.	1998	Automod + SIMAN		DES, structured methodology	Determine output of planned prod. Facility (Mercedes-Benz)
Kosturiak and Gregor	1999	Simple++	Several methods	New tools for dynamic decisions making. DES used for design, operation and continous improvement of complex manufact. systems	Sim. in production system lifecycle
Pidd	1994	(a summary)		Structured methodology	DES methods description + present summary on softwares available 1994
Knoll and Heim	2000			Strategies & methods to ensure successful adoption of DES	Characteristics of need for DES

Appendix 2: Discrete Event Simulation Software for Manufacturing Simulation

Simulation Software	Latest Version Number	Vendor
Arena	Version 7.0	Rockwell Software
AutoMod	Version 10.0 (Build 1600.94)	Brooks-PRI Automation Planning & Logistics Solutions
Enterprise Dynamics	Version 4.0	Incontrol Enterprise Dynamics
Extend	Version 5.0.4	Imagine That!
Flexsim ED	3.4	Flexsim Software Products
GPSS/H	Release 3.20-32	Wolverine Software
MicroSaint	Version 3.2	MicroAnalysis & Design
ProModel	2002	Promodel
QUEST	Release D5_41	Delmia
Silk	Version 1.3	ThreadTec
SIMPROCESS	Version 3.1	CACI Products Company
SIMUL8	Release 9	SIMUL8 Corporation
SLX	Version 0.99 (CT 311)	Wolverine Software
WITNESS	Version 2001a	Lanner Group

Source: http://www.systemflow.com/softvend.htm

Appendix 3: Production Data for First Research Case:

Production order file:

STATION BATCH FILE;;

---------------------------------------;;

Number of Batches in System:;4;
Number Of Varmup Batches:;1;

Sequence: ;	Variant;	No of parts	
1;	4;	4000	--Comment: Variant means crankshaft for
2;	4;	1000	-- either 4, 5, or 6 no. of cylinders engine
3;	6;	500	
4;	5;	500	
5;	5;	311	
6;	5;	1085	
7;	4;	215	
8;	4;	498	
9;	5;	273	
10;	5;	1099	
11;	4;	264	
12;	5;	349	
13;	5;	239	
14;	5;	1136	
15;	6;	246	
16;	4;	418	
17;	5;	639	
18;	4;	285	
19;	5;	372	
20;	5;	3500	

--Comment: repeated until batch 88

88;

Production Data File:

STATION SEQUENCE FILE;;;

---;;;

Number of Stations in System:;33;; --Comment: number of workcells in line

m_op_01_0;;4; --Comment: first workcell data

MTBD(in seconds).;288000;

MDT(in seconds):;8;

CellTime/part (in seconds):;31;

Number of WorkProcess;3;;

SetupTime (in seconds):;90;;

Number of Machines:;1;;

Process;Description;ProcTime;

-----------------------------------;;;

1;workprocess for complete pallet;609; --Comment: process time in seconds

2;workprocess for uncomplete pallet;31;

3;workprocess for packing lastpart;12;

m_op_10_1;;200; --Comment: This data is repeated for each workcell

MTBD(in seconds).;288000;

MDT(in seconds):;415;

CellTime/part (in seconds):;27;

Number of WorkProcess;3;;

SetupTime (in seconds):;44;;

Number of Machines:;1;;

Process;Description;ProcTime;

-----------------------------------;;;

1;workprocess for complete pallet;541;

2;workprocess for uncomplete pallet;27;

3;workprocess for packing part;12;

--Comment: repeated 31 times with individual data for each workcell

Appendix 4: Production Data for Third Research Case

Process time per lot in minutes

	Machine center									
Job type	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Lotsize**	**Jobmix**
1	2,6	2,4			2,4	4,8			2,4	4	0,2
2			2,3	2,9			4,5	6,8		4	0,1
3		4,1	5,2						4,4	6	0,12
4	5,6			6,7	4	12,8	9,1			8	0,1
5		5,4		7,9					4,8	8	0,08
6	5,2	6,6		6,7			9,9	12,0		8	0,04
7		2,4	2,3		2,4				2,9	4	0,12
8	1,4			2,0				3		2	0,06
9			1,7					3,4	1,5	2	0,12
10	3,9	4,1		5						6	0,06